

The freeze-out source shape: recent results from the STAR energy scan

Mike Lisa (Ohio State University)
for the STAR Collaboration



Outline

- general motivation
 - RHIC BES program
 - asHBT
- a growing database of asHBT systematics
 - (another) anomalous behaviour at SPS?
 - new STAR data
 - reconciling RHIC, SPS results?
 - centrality cuts
 - RP resolution correction schemes
 - rapidity (underway)
- conclusion



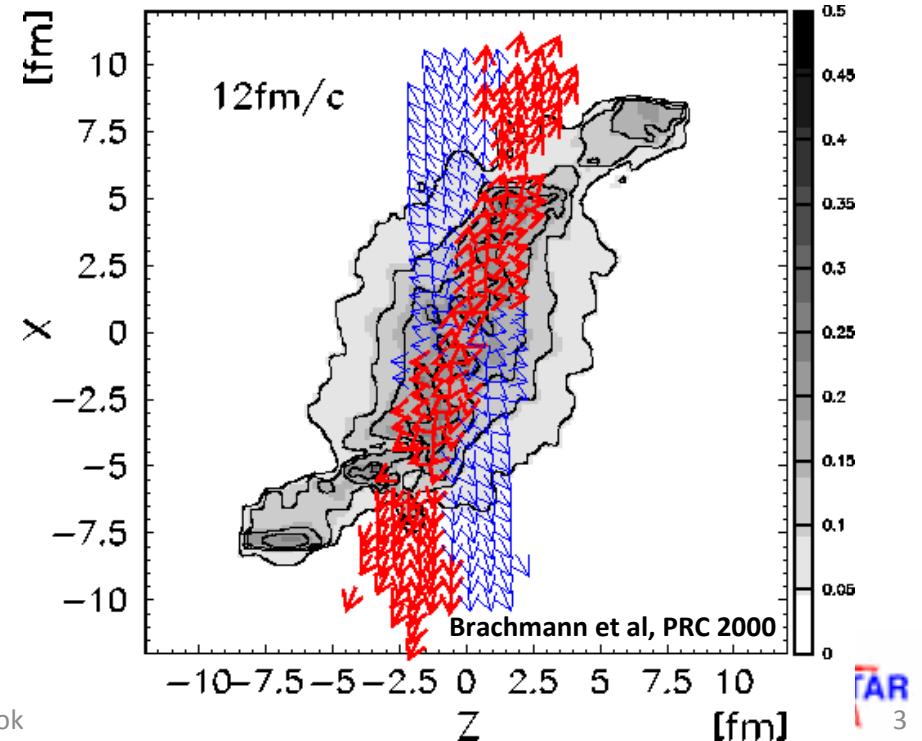
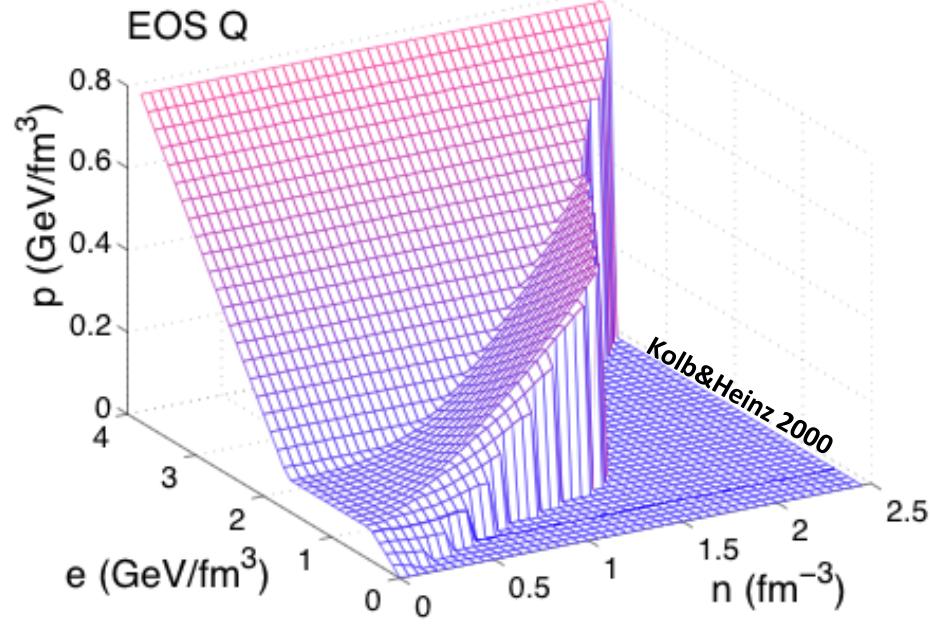
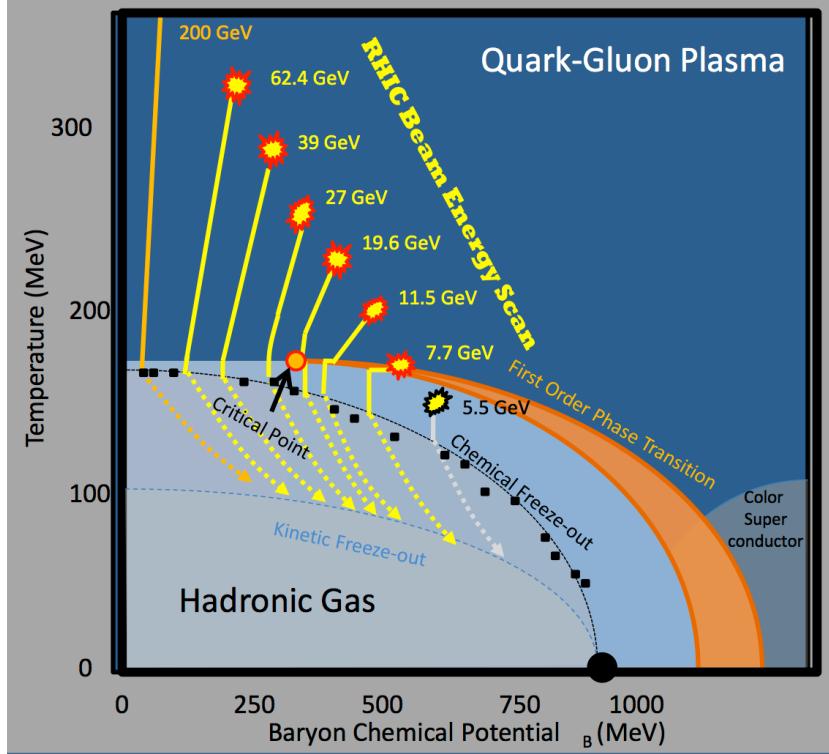
RHIC energy scan: $\sqrt{s}=7\text{-}40 \text{ GeV}$ (2010~2012 (?))

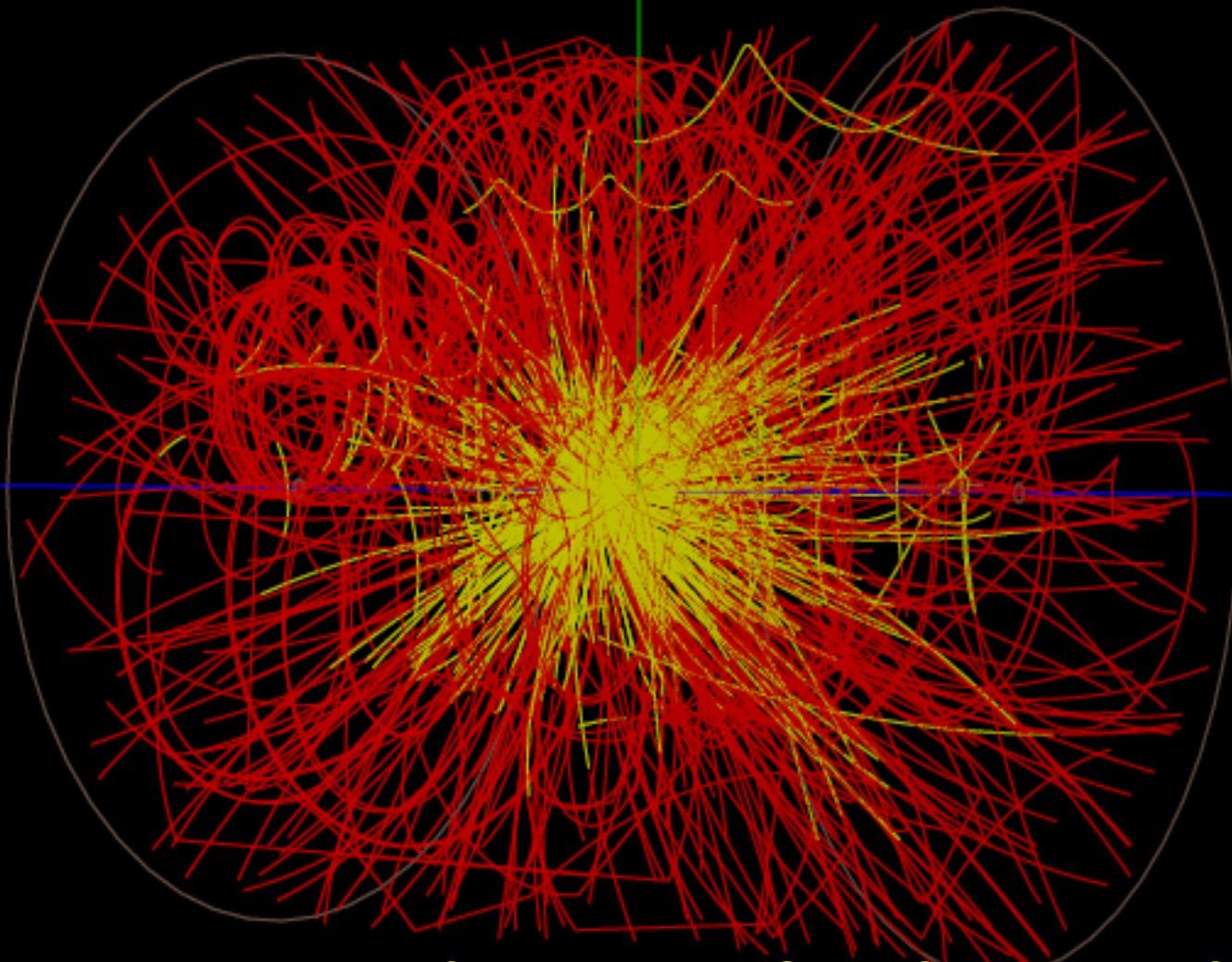
Probe QCD phase diagram via

- statistics/fluctuations

✓ dynamic system response

- transport models (phase structure in EoS)
- bulk collectivity (low- p_T measurements)





Central Au+Au @ 7.7 GeV event in STAR TPC

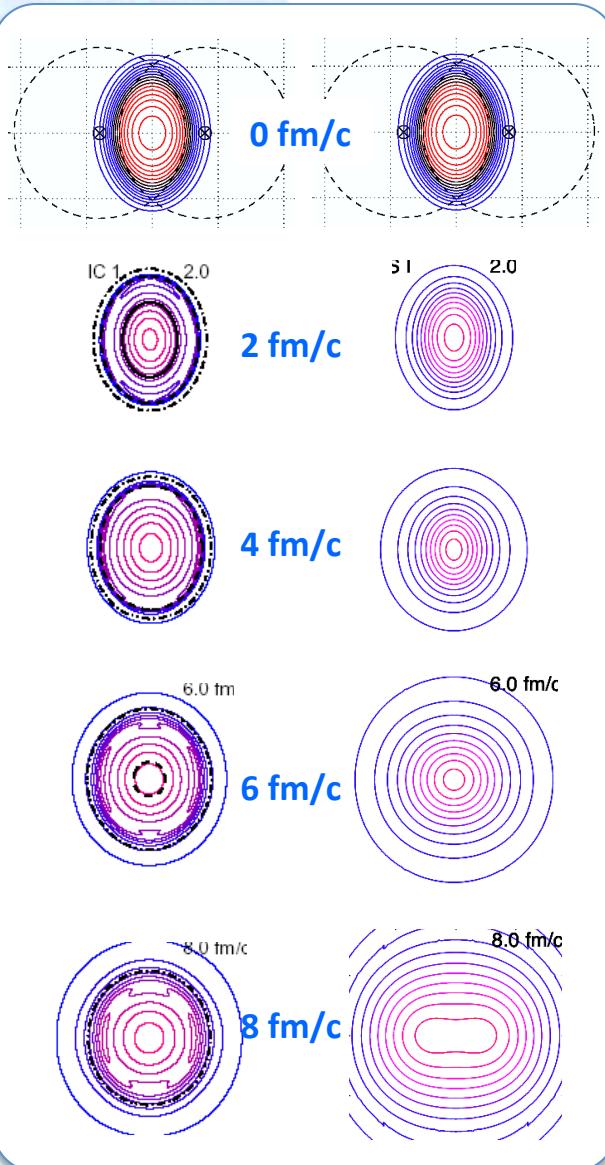
Collision Energies (GeV)	5	7.7	11.5	17.3	27	39
Observables	Millions of Events Needed					
v_2 (up to ~ 1.5 GeV/c)	0.3	0.2	0.1	0.1	0.1	0.1
v_1	0.5	0.5	0.5	0.5	0.5	0.5
Azimuthally sensitive HBT	4	4	3.5	3.5	3	3
PID fluctuations (K/π)	1	1	1	1	1	1
net-proton kurtosis	5	5	5	5	5	5
differential corr & fluct vs. centrality	4	5	5	5	5	5
n_q scaling $\pi/\text{K}/\rho/\Lambda\mu\beta\delta\alpha$ $(m_T - m_0)/n < 2 \text{ GeV}$	8.5	6	5	5	4.5	4.5
$\pi\eta/\Omega\epsilon\gamma$ to $p_T/n_q = 2$ GeV/c		56	25	18	13	12
R_{CP} up to $p_T \sim 4.5$ GeV/c (at 17.3) 5.5 (at 27) & 6 GeV/c (at 39)				15	33	24
untriggered ridge correlations		27	13	8	6	6
parity violation		5	5	5	5	5

Status as of Oct 5 2011

Collision Energies (GeV)	5	7.7	11.5	17.3	19.6	27	39
Mevents taken (2010/11)		~5	~11	~17	~37	~170	
Observables	Millions of Events Needed						
v_2 (up to ~ 1.5 GeV/c)	0.3	0.2	0.1	0.1	0.1	0.1	
v_1	0.5	0.5	0.5	0.5	0.5	0.5	
Azimuthally sensitive HBT	4	4	3.5	3.5	3	3	
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differential corr & fluct vs. centrality (e.g. bal. fctn)	4	5	5	5	5	5	
n_q scaling $\pi/\text{K}/\text{p}/\Lambda\alpha\mu\beta\delta\alpha$ $(m_T - m_0)/n < 2 \text{ GeV}$	8.5	6	5	5	4.5	4.5	
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parity violation		5	5	5	5	5	



phi- the sexy direction



evolution from initial “known” shape depends on

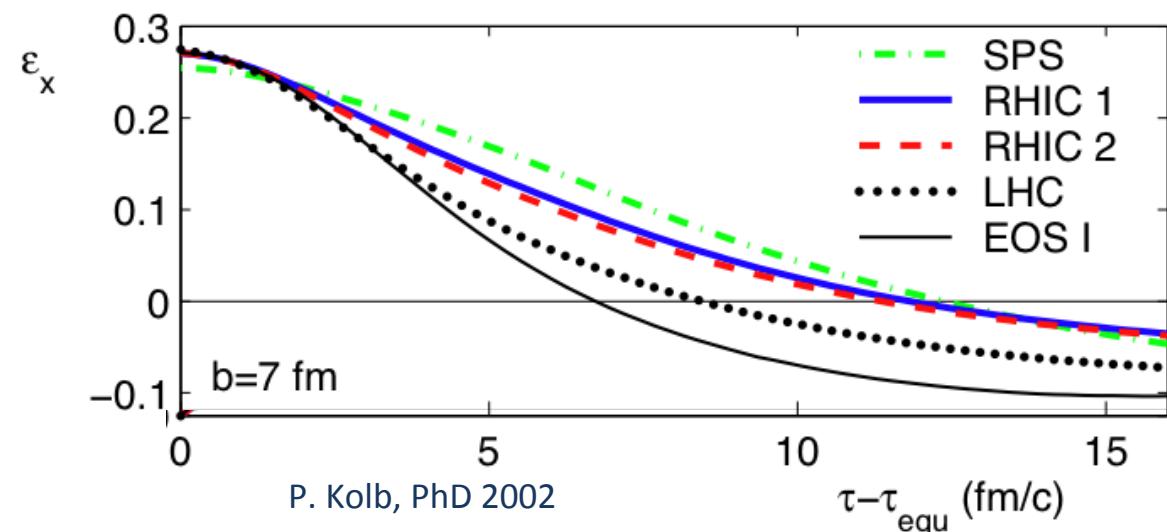
- pressure anisotropy (“stiffness”)
- lifetime

Both are interesting!

We will measure a convolution over freezeout

- model needed

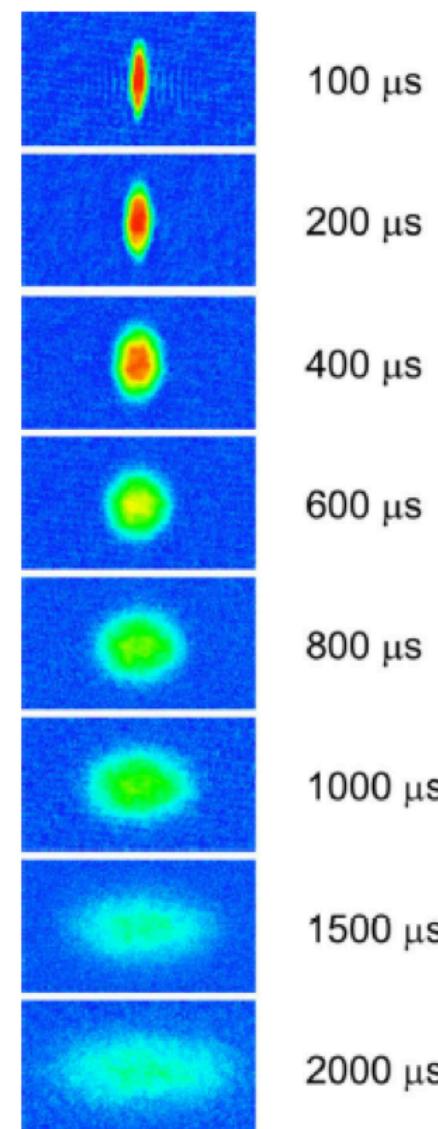
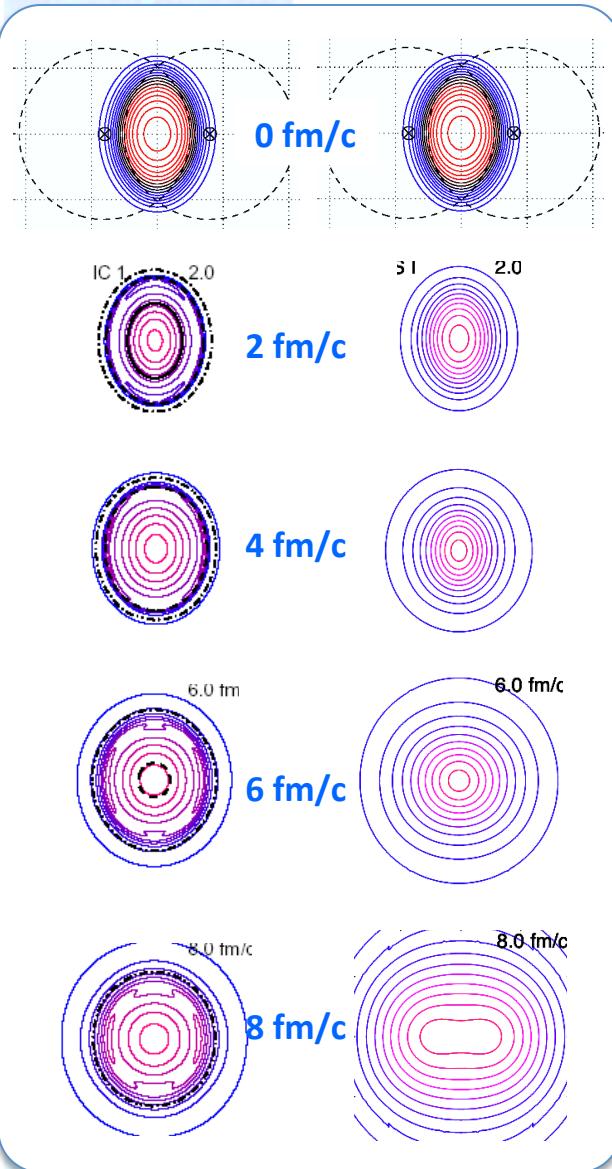
$$\varepsilon \equiv \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$



P. Kolb, PhD 2002

$\tau - \tau_{\text{equ}}$ (fm/c)

phi- the sexy direction



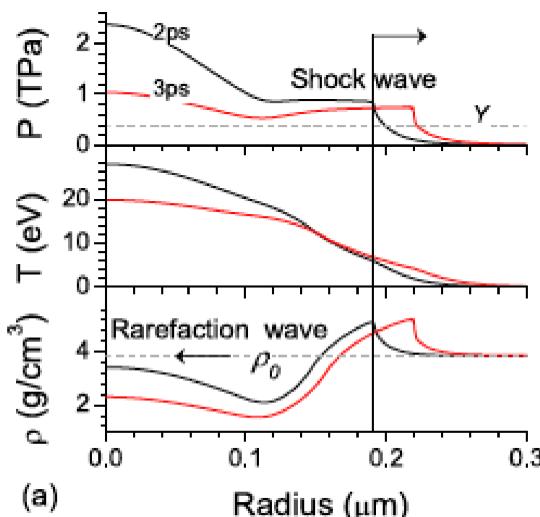
O'Hara et al, *Science* 2002

Laser-Induced Microexplosion Confined in the Bulk of a Sapphire Crystal: Evidence of Multimegarbar Pressures

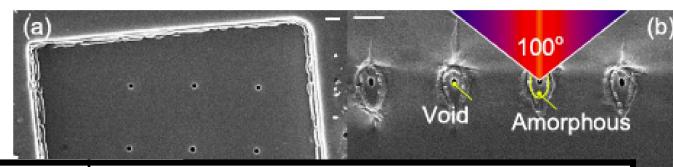
S. Inodukzis¹ K. Nishimura¹ S. Tanaka¹ H. Misawa¹ E. G. Gamaly² R. Luther-Davies²

Extremely high pressures (~ 10 TPa) and temperatures (5×10^5 K) have been produced using a single laser pulse (100 nJ, 800 nm, 200 fs) focused inside a sapphire crystal. The laser pulse creates an intensity over 10^{14} W/cm² converting material within the absorbing volume of $\sim 0.2 \mu\text{m}^3$ into plasma in a few fs. A pressure of ~ 10 TPa, far exceeding the strength of any material, is created generating strong shock and rarefaction waves. This results in the formation of a nanovoid surrounded by a shell of shock-affected material inside undamaged crystal. Analysis of the size of the void and the shock-affected zone versus the deposited energy shows that the experimental results can be understood on the basis of conservation laws and be modeled by plasma hydrodynamics. Matter subjected to record heating and cooling rates of 10^{18} K/s can, thus, be studied in a well-controlled laboratory environment.

studied in a well-controlled laboratory environment.



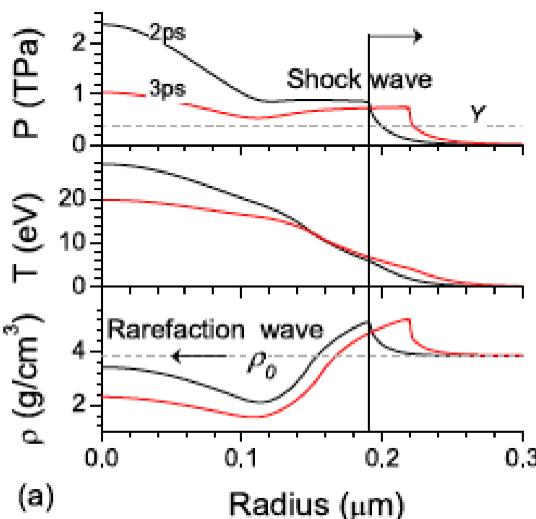
	Microexplosions	Femtoexplosions
\sqrt{s}	$0.1 \mu\text{J}$	$1 \mu\text{J}$
ϵ	10^{17} J/m^3	$5 \text{ GeV/fm}^3 = 10^{36} \text{ J/m}^3$
T	10^6 K	$200 \text{ MeV} = 10^{12} \text{ K}$
rate	10^{18} K/sec	10^{35} K/s



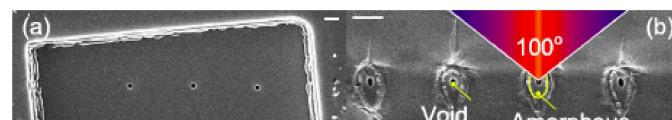
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- energy quickly deposited
- transition to deconfined (plasma) phase
- hydrodynamic expansion
- cool back to confined (atomic) phase

Laser-Induced Microexplosion Confined in the Bulk of a Sapphire Crystal:
 PHYSICAL REVIEW B 76, 024101 (2007)
 Evidence of Multimegarab Pressures

Model and numerical simulations of the propagation and absorption of a short laser pulse in a transparent dielectric material: Blast-wave launch and cavity formation

Ludovic Hallo,^{1,*} Antoine Bourgeade,² Vladimir T. Tikhonchuk,¹ Candice Mezel,¹ and Jérôme Breil¹

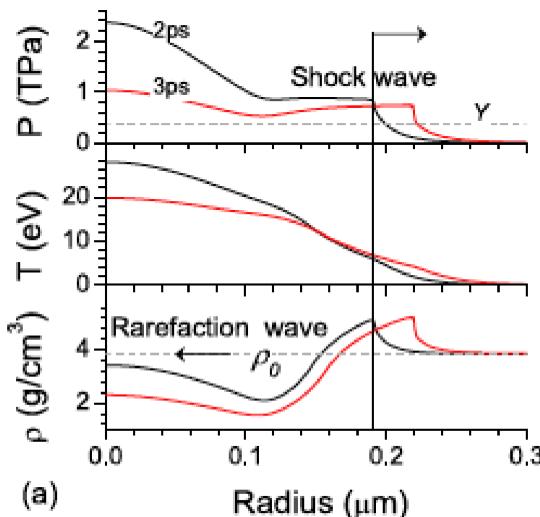
¹Université Bordeaux 1, CNRS, CEA, UMR 5107, 33405 Talence Cedex, France

²CEA-CESTA, BP 1, 33114 Le Barp, France

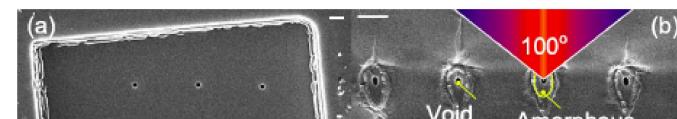
(Received 30 March 2007; published 2 July 2007)

Extremely high pressures and temperatures ($\sim 10^{18}$ K) are induced in a volume of $\sim 0.2 \mu\text{m}^3$ into plasma in a few fs. The energy deposited by the laser pulse, which is the strength of any material, is created generating strong shock and rarefaction waves. This results in the formation of a nanovoid surrounded by a shell of shock-affected material inside undamaged crystal. Analysis of the size of the void and the shock-affected zone versus the deposited energy shows that the experimental results can be understood on the basis of conservation laws and be modeled by **plasma hydrodynamics**. Matter subjected to record heating and cooling rates of 10^{18} K/s can, thus, be studied in a well-controlled laboratory environment.

studied in a well-controlled laboratory environment.



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Formation of nanocavities in dielectrics: influence of equation of state

L. Hallo · A. Bourgeade · C. Mézel · G. Travaillet · D. Hébert · B. Chimier · G. Schurtz · V.T. Tikhonchuk

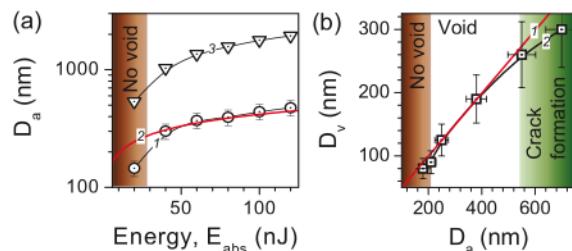


FIG. 3 (color). (a) The diameter (1) and length (3) of the amorphous region vs the absorbed pulse energy, E_{abs} . The voids were 20 μm beneath the surface. Curve (2) plotted by Eq. (1) with $l_a = 80 \text{ nm}$. (b) Dependence of the void diameter on the diameter of amorphous part: (1) theory by Eq. (2) with $\delta = 1.14$; (2) experiment.

data should allow a tuning of equations of state in main of extreme parameters

Table 1 SESAME 7387, QEOS and home-made IL type EOS parameters

EOS name	G	E_{sub} (MJ/kg)
QEOS	1.5	≈0.01
SESAME 7387	0.65	10
IL0005	0.03	17
IL0006	0.03	28
IL0007	0.03	8

Published online: 28 Ma

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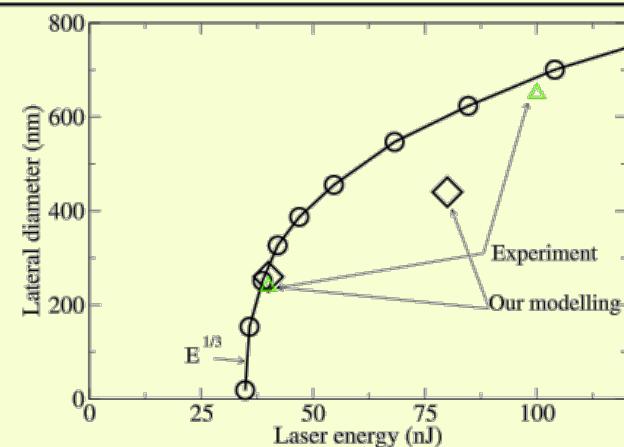


Fig. 9 Cavity diameter on the laser energy in silica, simple modeling (circles) [2], IL0005 EOS (diamond shapes) and experiment (triangles)

- energy quickly deposited
- transition to deconfined (plasma) phase
- hydrodynamic expansion
- cool back to confined (atomic) phase
- probe EoS under extreme conditions (**vs dep.**)

Microexplosion

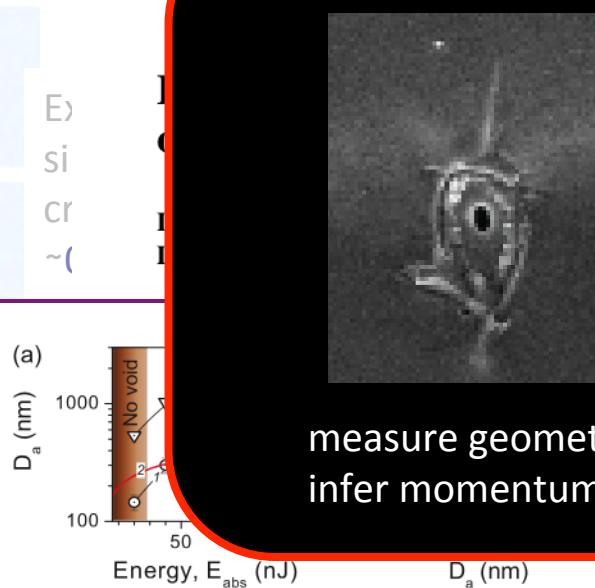


FIG. 3 (color). (a) The diameter (1) and length (3) of the amorphous region vs the absorbed pulse energy, E_{abs} . The voids were 20 μ m beneath the surface. Curve (2) plotted by Eq. (1) with $l_a = 80$ nm. (b) Dependence of the void diameter on the diameter of amorphous part: (1) theory by Eq. (2) with $\delta = 1.14$; (2) experiment.

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Femtoexplosion

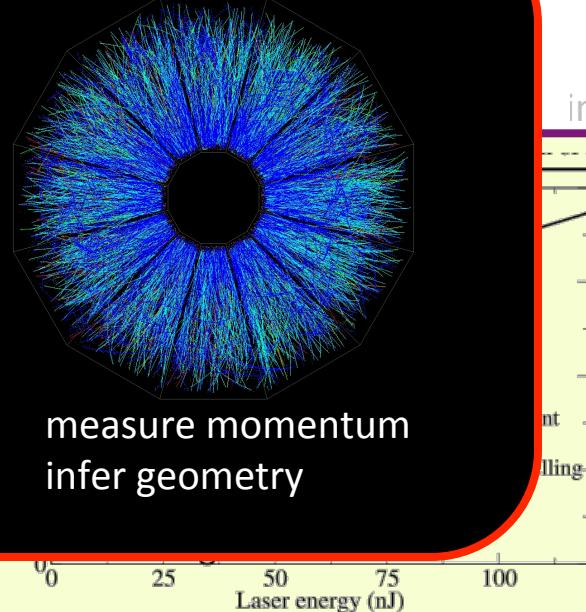
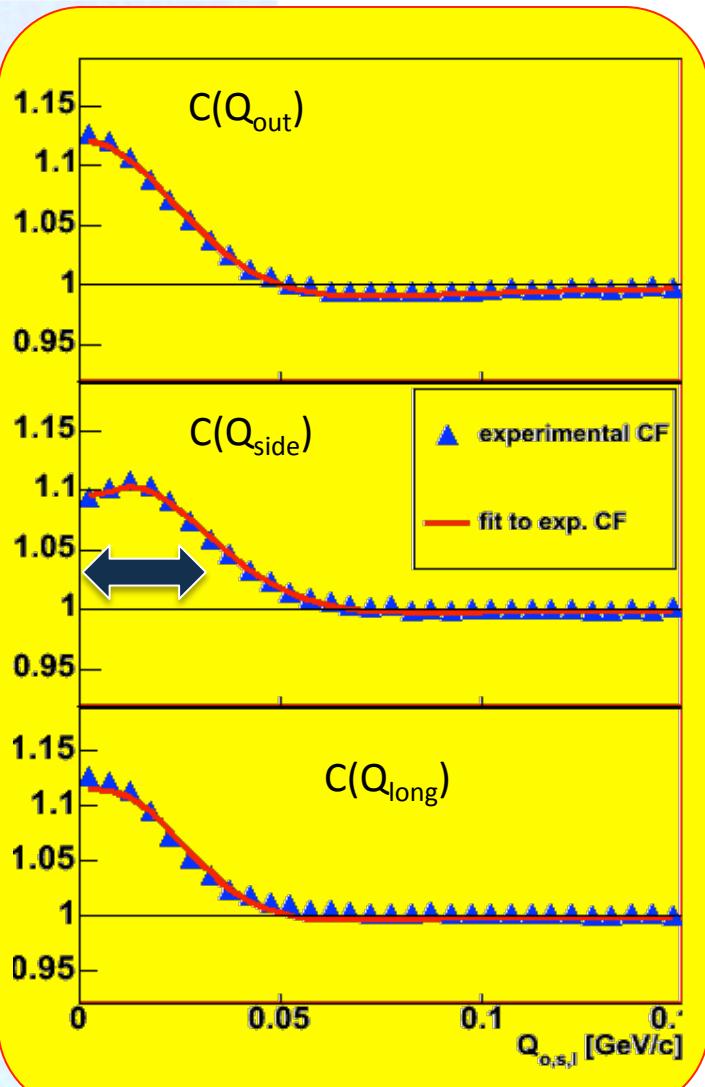


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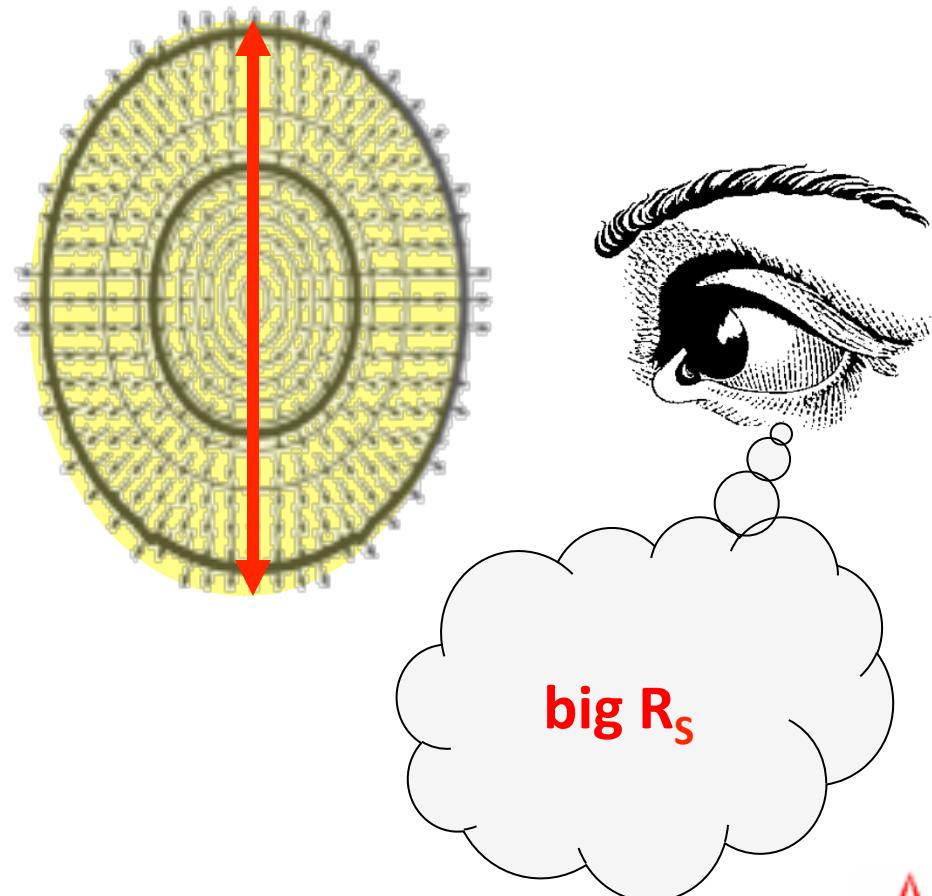
- energy quickly deposited
- transition to deconfined (plasma) phase
- hydrodynamic expansion
- cool back to confined (atomic) phase
- probe EoS under extreme conditions (**vs dep.**)
- examine final shape/size of system

measuring lengths

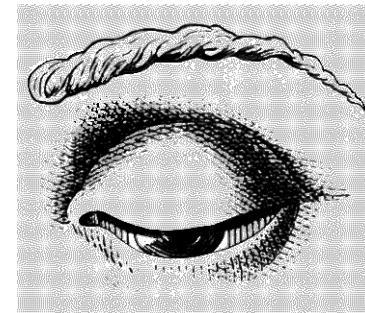
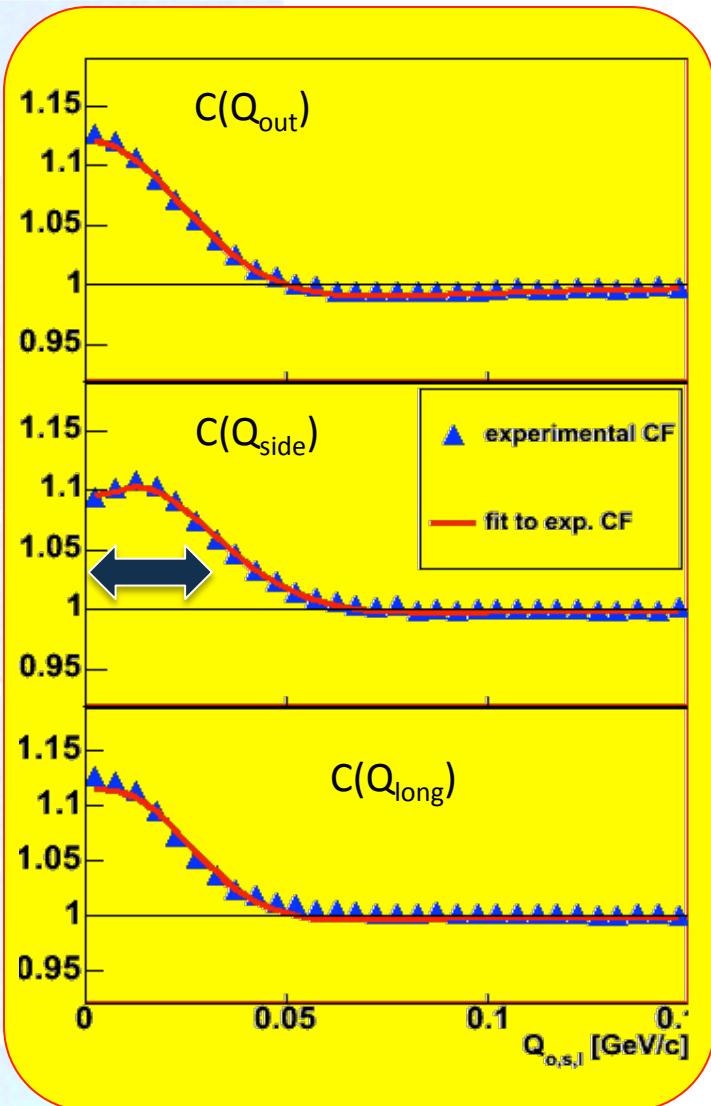


$$C(\vec{q}) = N \cdot \left[1 + \lambda \cdot \left(K_{\text{coul}}(\vec{q}) \cdot \left\{ 1 + e^{-\left(q_o^2 R_o^2 + q_s^2 R_s^2 + q_l^2 R_l^2 \right)} \right\} - 1 \right) \right]$$

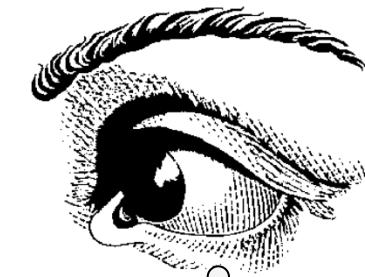
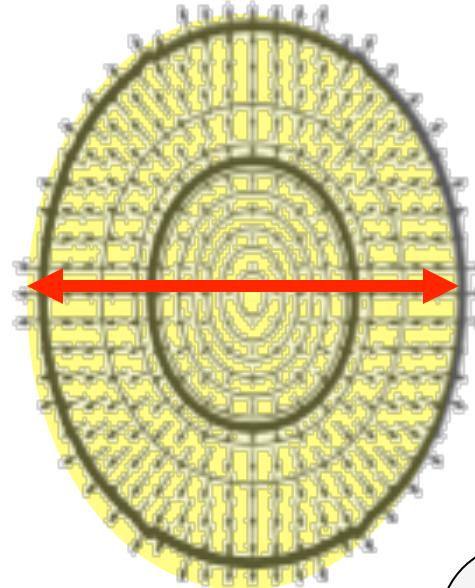
typical “Gaussian” fitting function



measuring shape

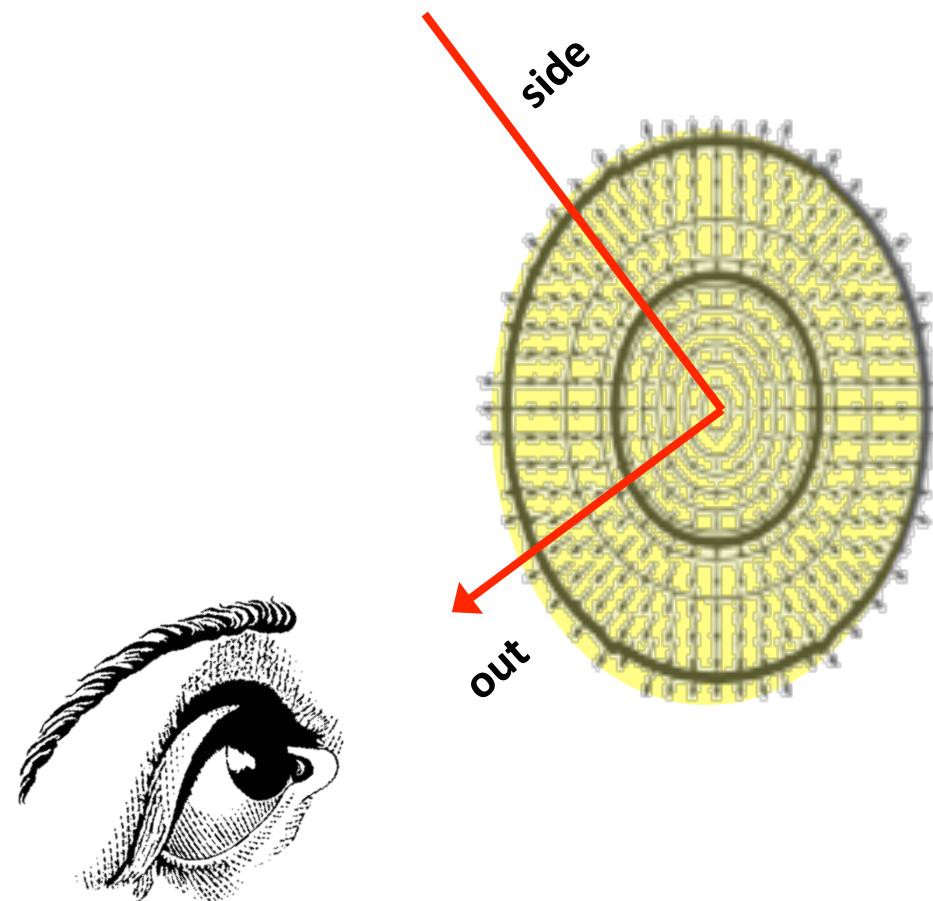


small R_s



big R_s

measuring shape

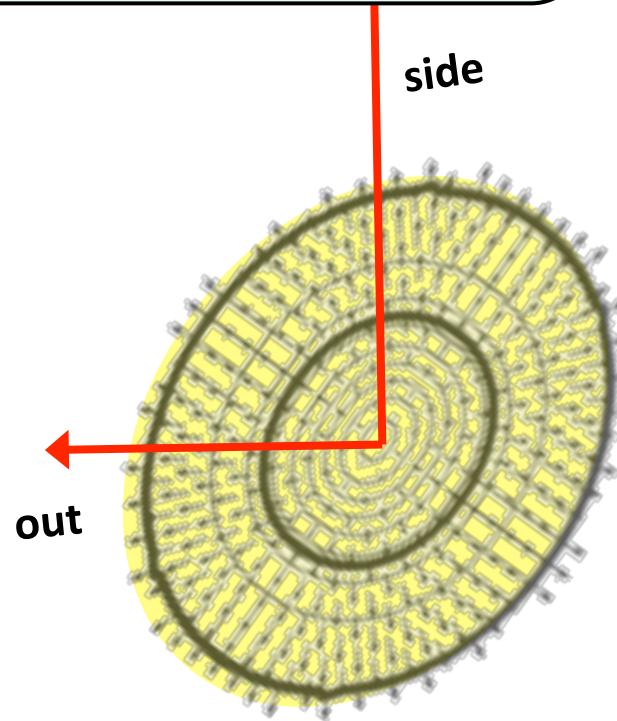


measuring shape

$$C(\vec{q}) = N \cdot \left[1 + \lambda \cdot \left(K_{coul}(\vec{q}) \cdot \left\{ 1 + \exp(-\textcolor{red}{q_i q_j R_{ij}^2}) \right\} - 1 \right) \right]$$

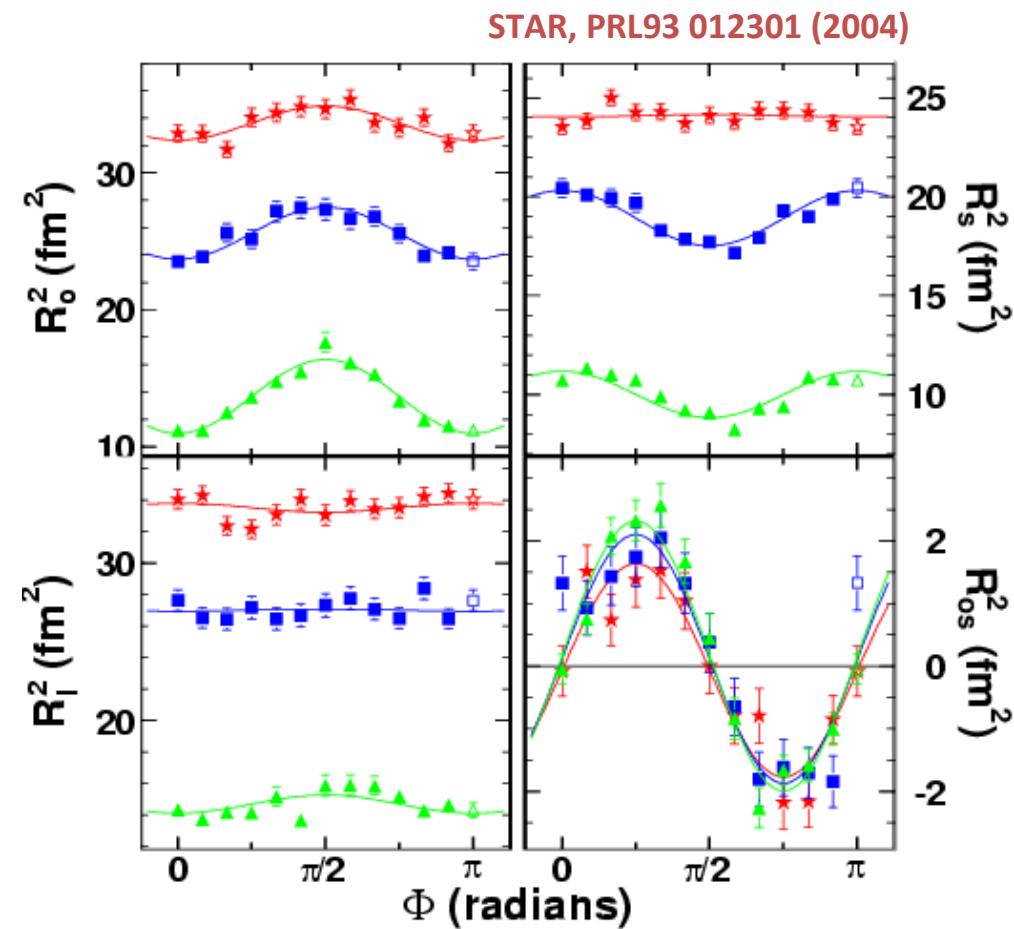
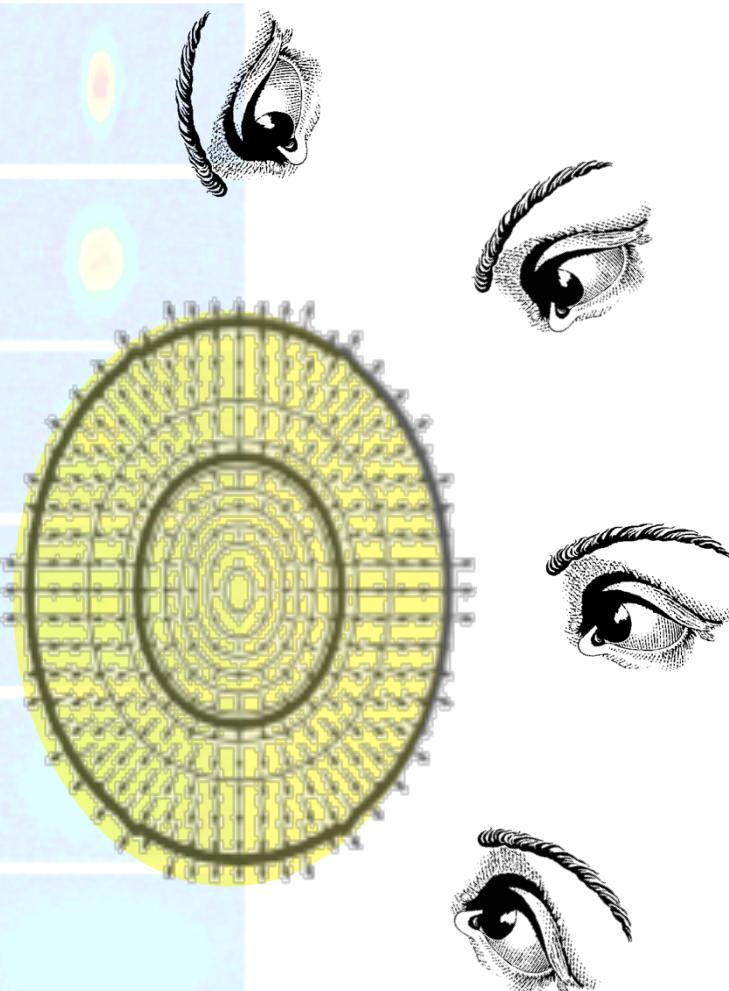
more info. six “HBT radii”

$$R_o^2, R_s^2, R_l^2, \textcolor{blue}{R}_{os}^2, R_{sl}^2, R_{ol}^2$$



$R^2_{\text{out-side}} < 0$

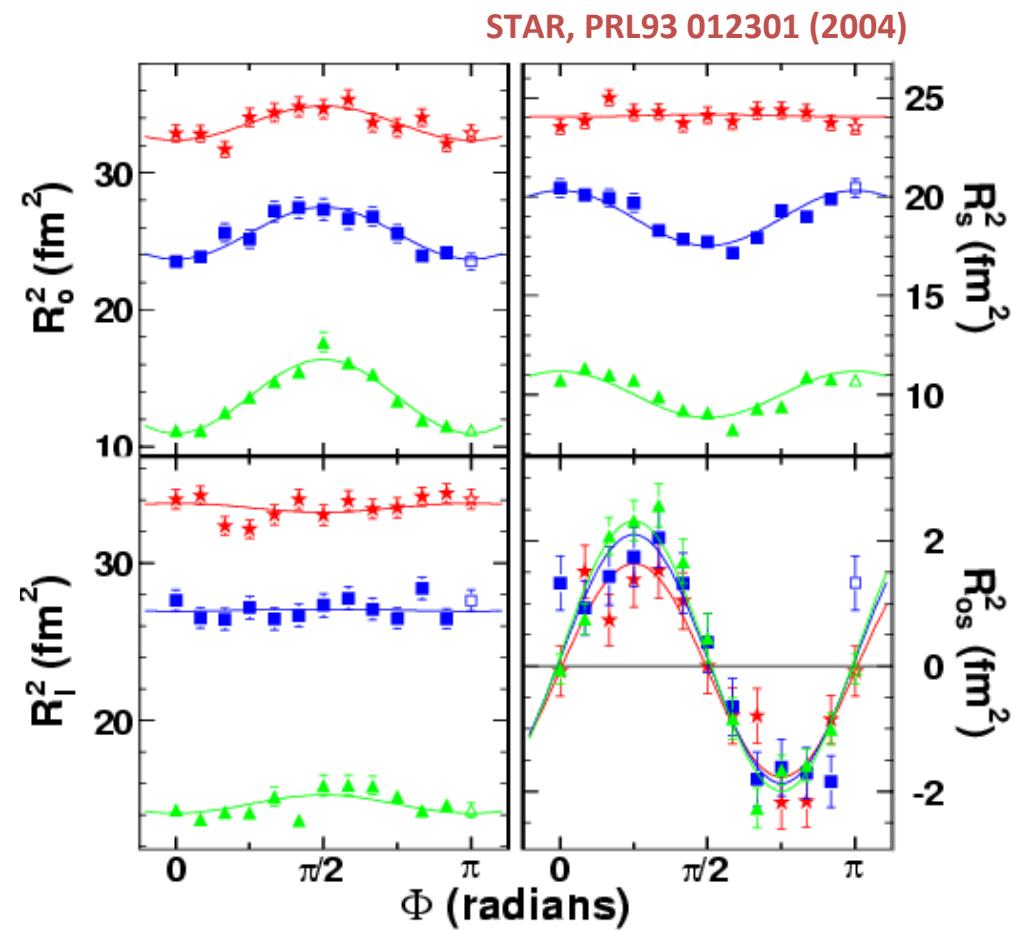
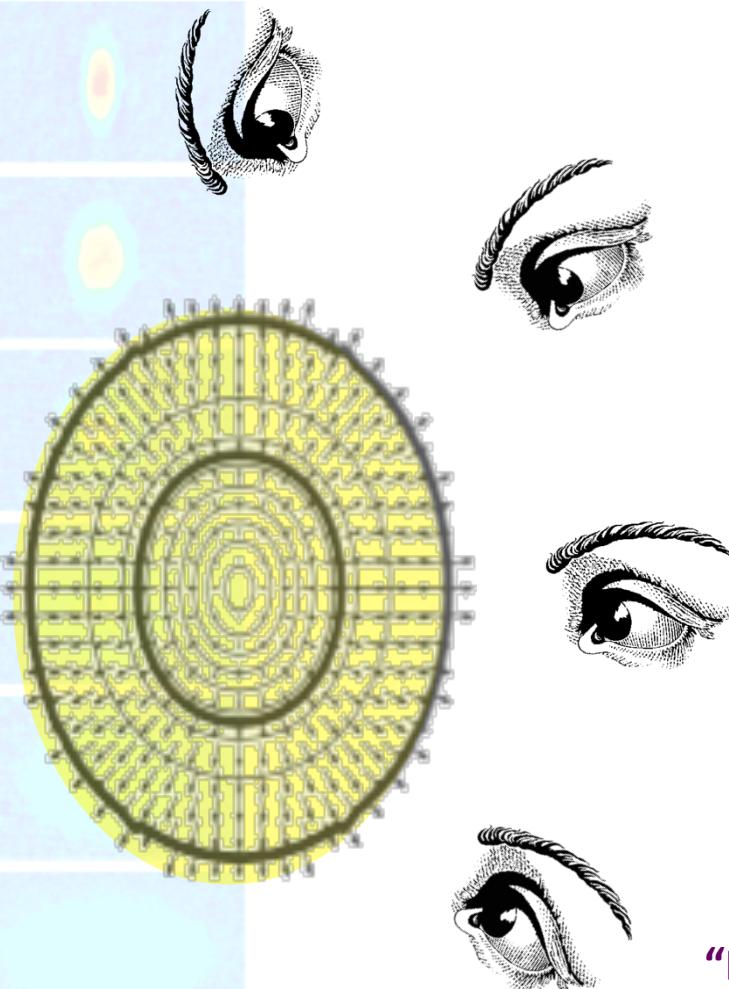
Azimuthal dependence of HBT radii at RHIC



$$R_{s,n}^2 \equiv \langle R_s^2(\phi) \cdot \cos(n\phi) \rangle \quad \varepsilon \approx 2 \frac{R_{s,2}^2}{R_{s,0}^2} \approx 2 \frac{R_{os,2}^2}{R_{s,0}^2} \approx -2 \frac{R_{os,2}^2}{R_{s,0}^2}$$

Retiere&MAL PRC70 (2004) 044907

Azimuthal dependence of HBT radii at RHIC

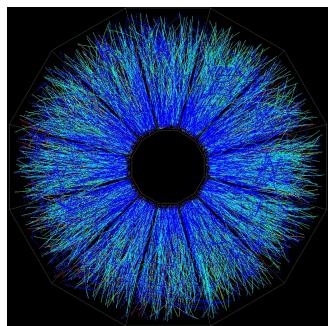


"No-flow formula" estimated good within ~ 30% (low pT)

Retiere&MAL PRC70 (2004) 044907
Mount et al, PRC84:014908,2011

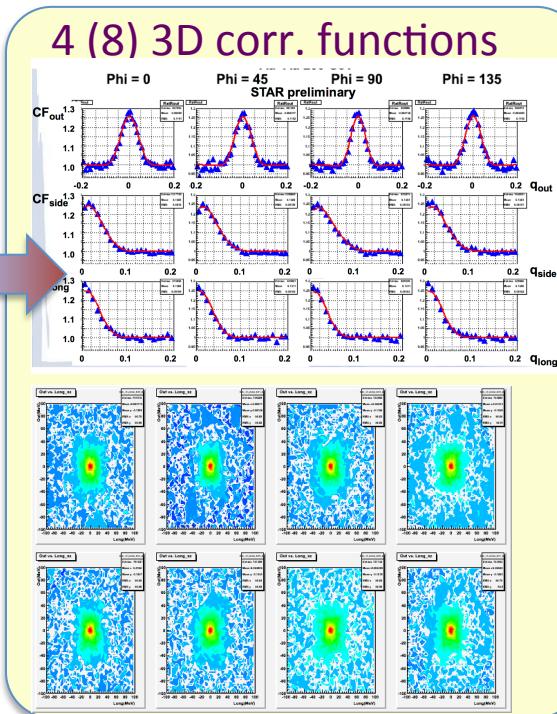
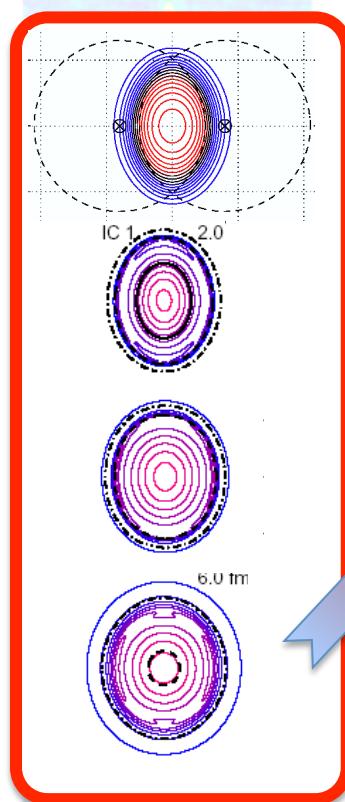
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Welcome to the machine

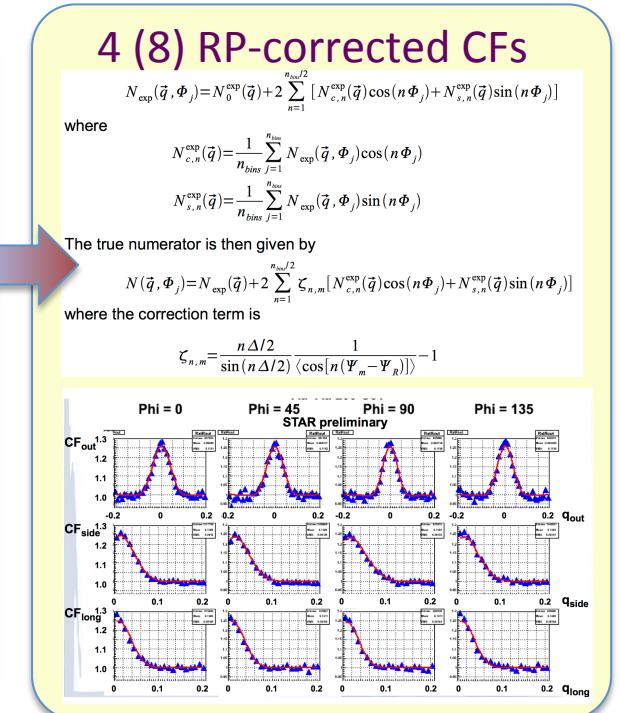
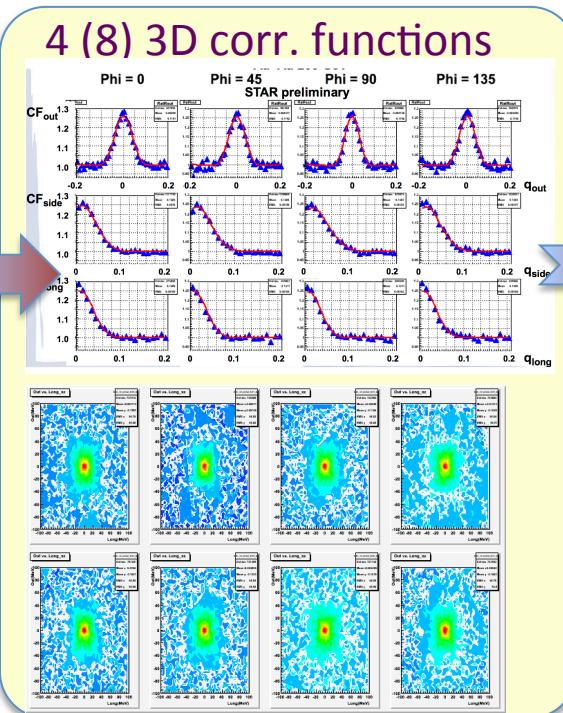
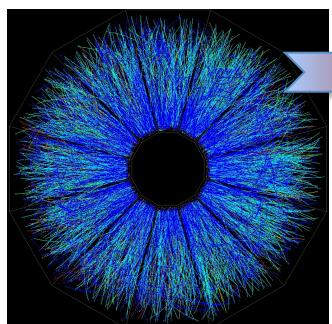
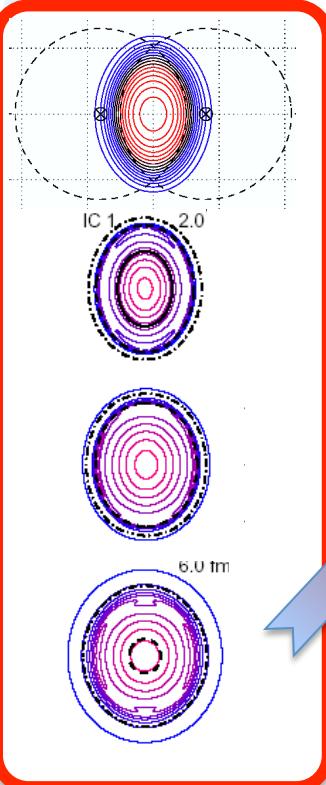


It's a bit more complicated than
using a microscope like the
femtosecond laser guys do...

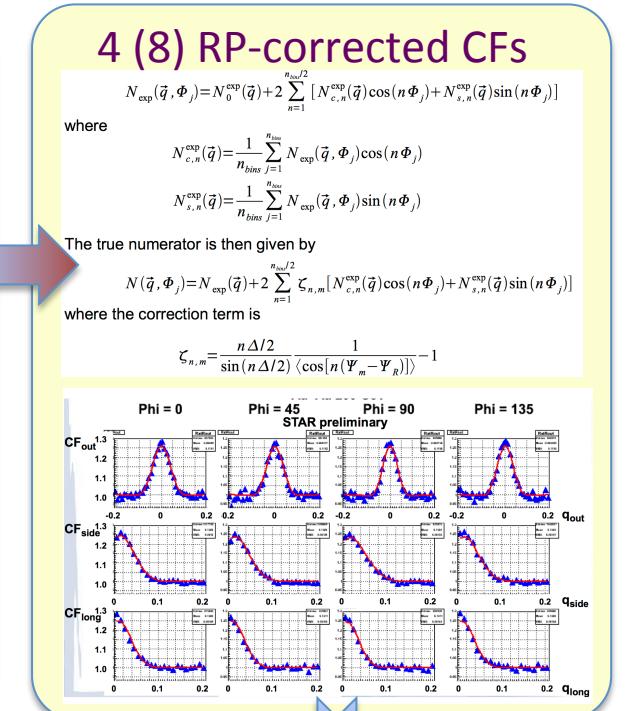
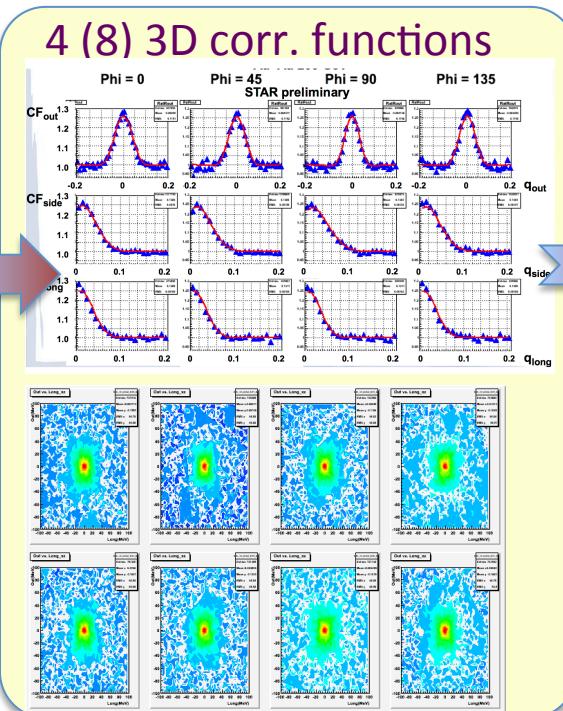
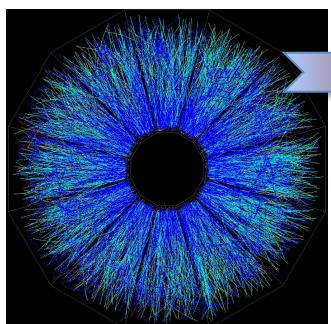
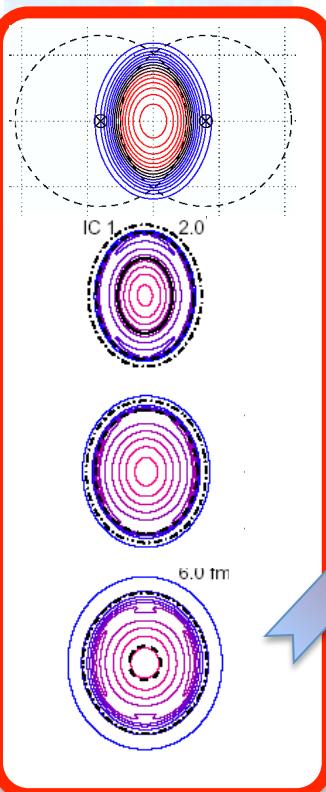
Welcome to the machine



Welcome to the machine

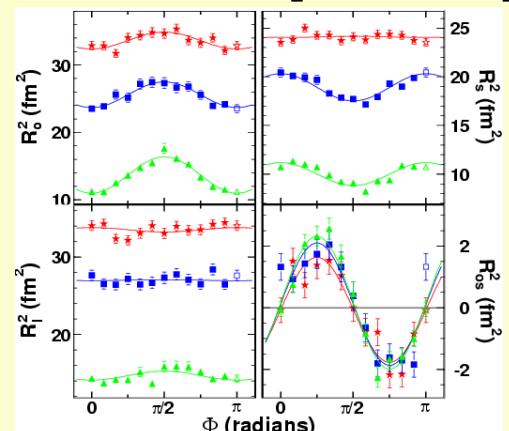


Welcome to the machine

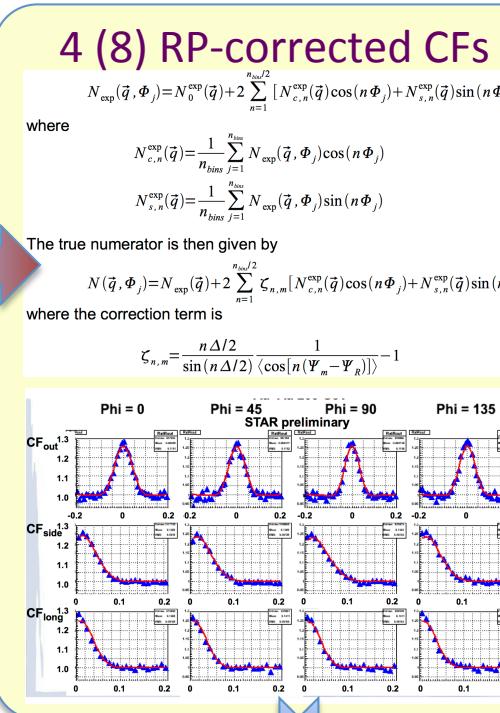
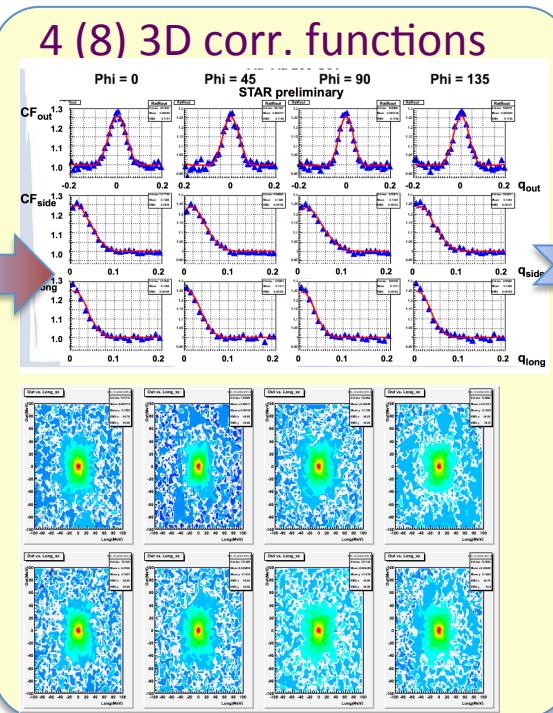
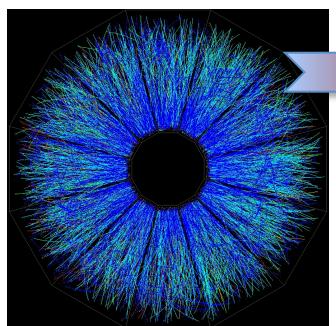
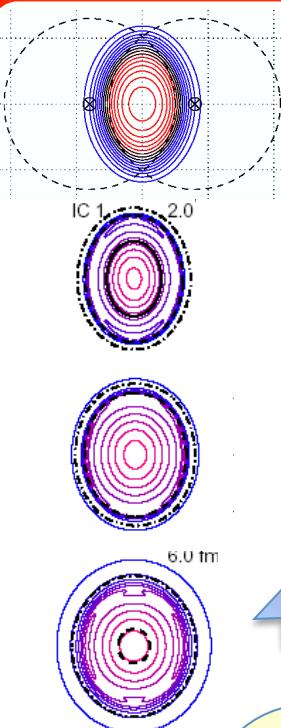


4 (8) sets of 4 (6) radii

$$C^{\text{fit}}(\vec{q}) = 1 + \lambda \exp \left[- \sum_{i,j=o,s,l} q_i q_j R_{i,j}^2 \right]$$

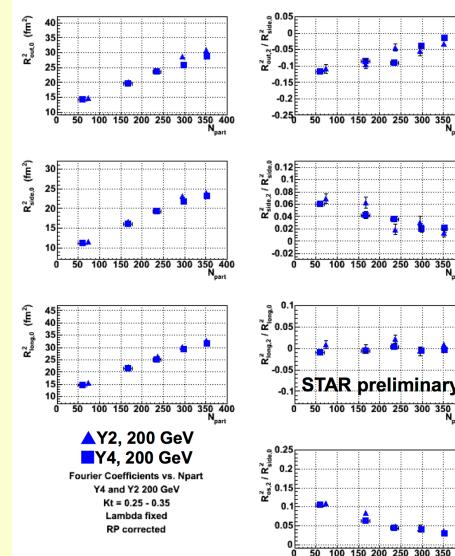


Welcome to the machine



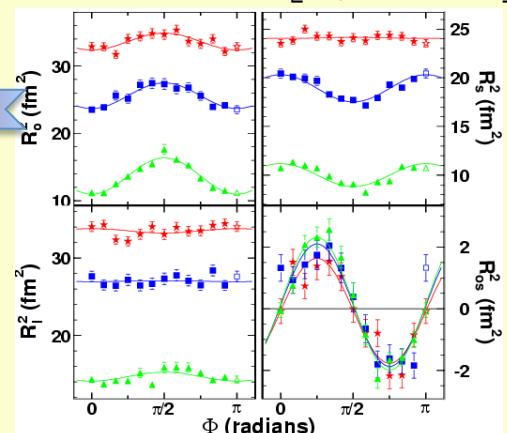
7 (9) Fourier Coefficients

$$R_{ij,n}^2 = \left\langle R_{ij}^2(\phi) \left\{ \begin{array}{l} \sin n\phi \\ \cos n\phi \end{array} \right\} \right\rangle$$

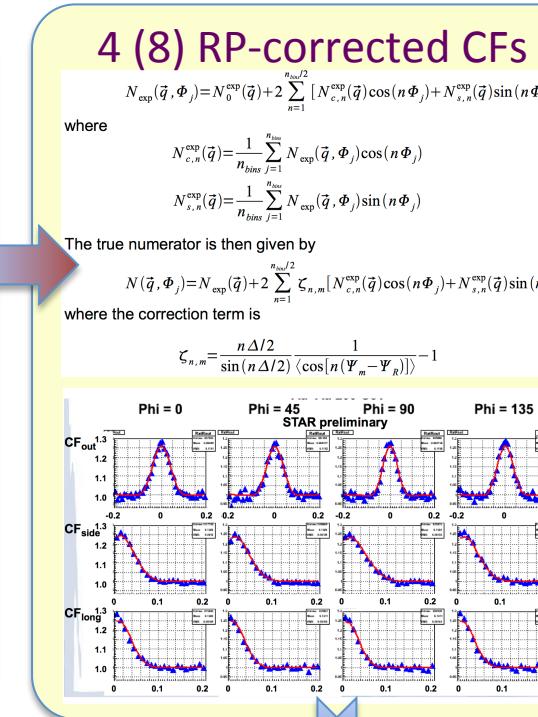
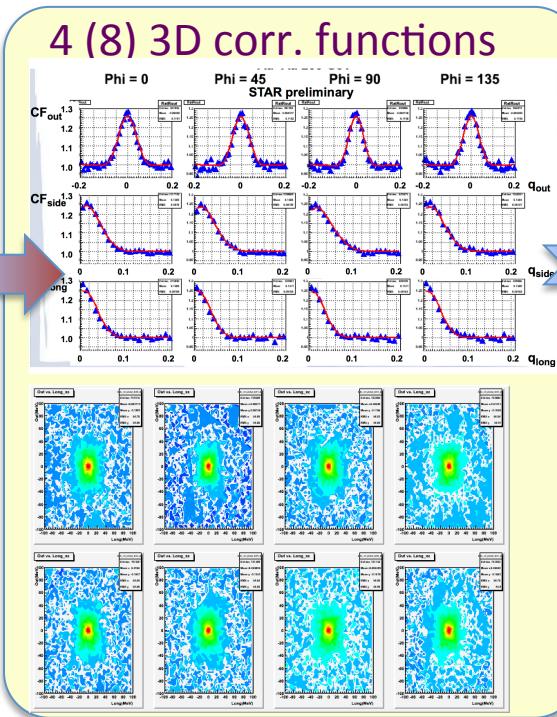
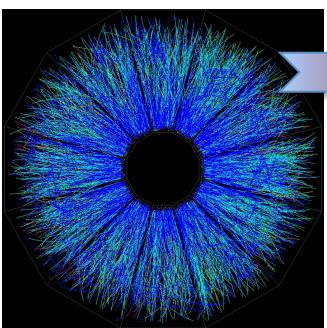
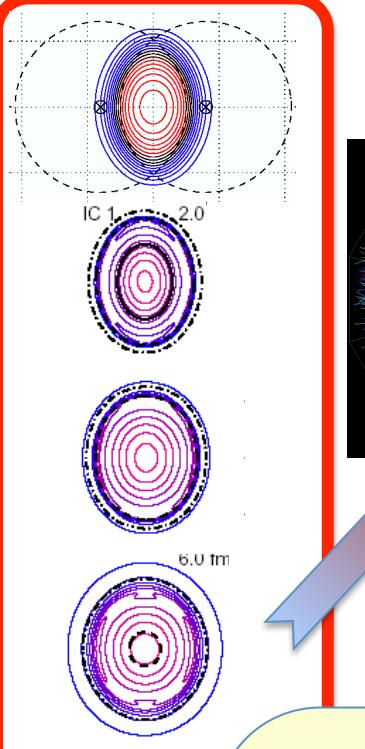


4 (8) sets of 4 (6) radii

$$C^{fit}(\vec{q}) = 1 + \lambda \exp \left[- \sum_{i,j=o,s,l} q_i q_j R_{i,j}^2 \right]$$

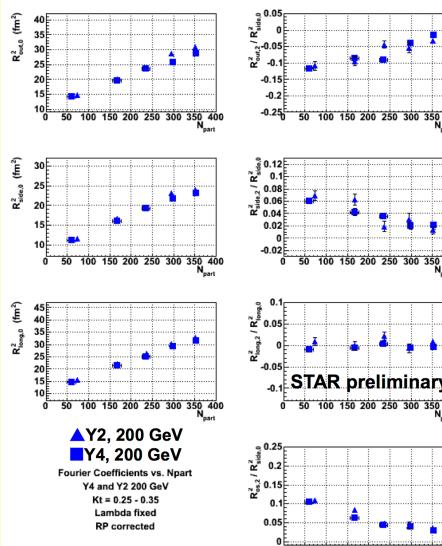


Welcome to the machine



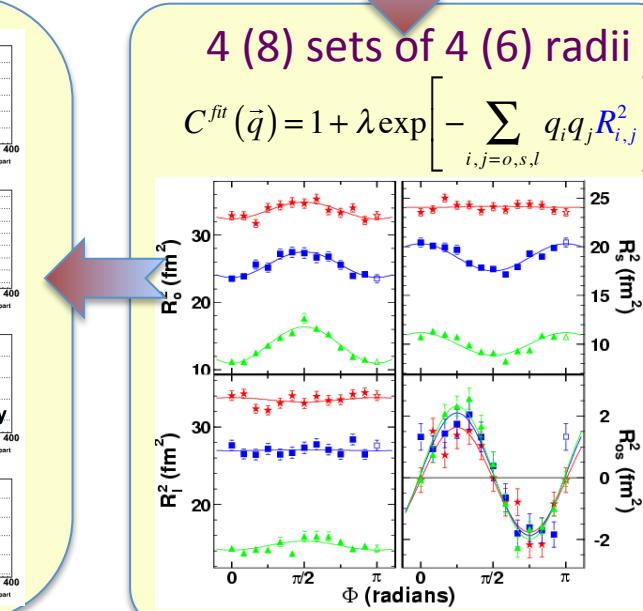
7 (9) Fourier Coefficients

$$R_{ij,n}^2 = \left\langle R_{ij}^2(\phi) \left\{ \begin{array}{l} \sin n\phi \\ \cos n\phi \end{array} \right\} \right\rangle$$

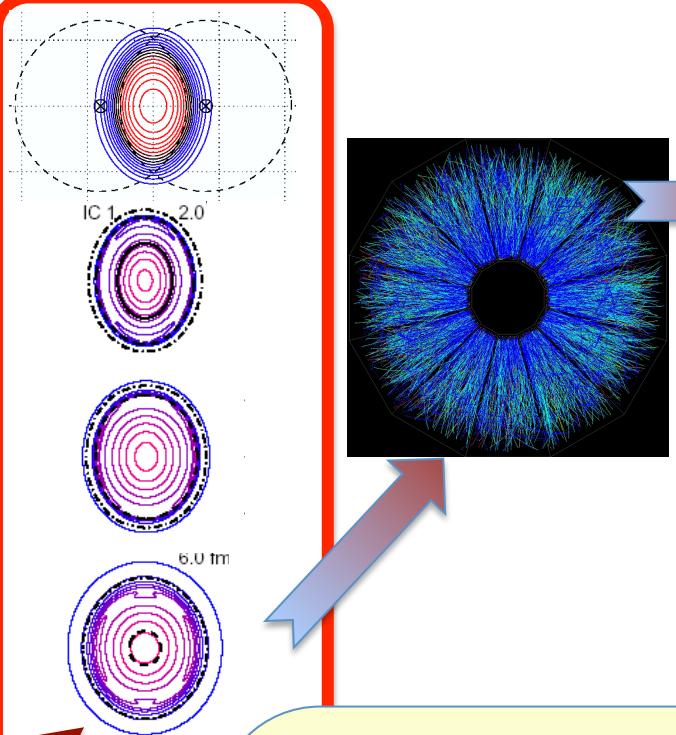


1 eccentricity estimate

$$\epsilon = 2 \frac{R_{s,2}^2}{R_{s,0}^2}$$



Welcome to the machine



7 (9) Fourier Coefficients

$$R_{ij,n}^2 = \left\langle R_{ij}^2(\phi) \left\{ \begin{array}{c} \sin n\phi \\ \cos n\phi \end{array} \right\} \right\rangle$$

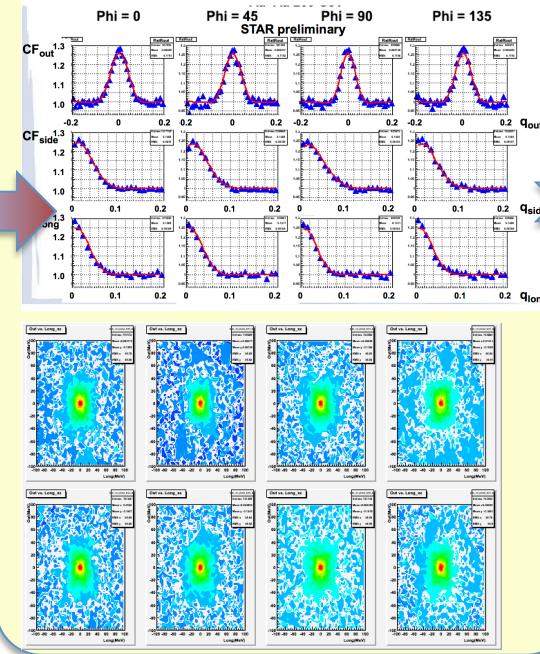
~30%

1 eccentricity estimate

$$\varepsilon = 2 \frac{R_{s,2}^2}{R_{s,0}^2}$$

see, e.g. E. Mount et al PRC84:014908, 2011

4 (8) 3D corr. functions



4 (8) RP-corrected CFs

$$N_{exp}(\vec{q}, \Phi_j) = N_0^{exp}(\vec{q}) + 2 \sum_{n=1}^{n_{bin}/2} [N_{c,n}^{exp}(\vec{q}) \cos(n\Phi_j) + N_{s,n}^{exp}(\vec{q}) \sin(n\Phi_j)]$$

where

$$N_{c,n}^{exp}(\vec{q}) = \frac{1}{n_{bins}} \sum_{j=1}^{n_{bin}} N_{exp}(\vec{q}, \Phi_j) \cos(n\Phi_j)$$

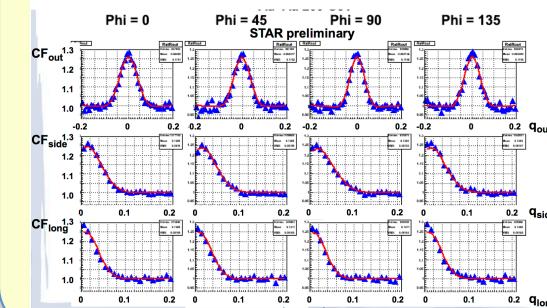
$$N_{s,n}^{exp}(\vec{q}) = \frac{1}{n_{bins}} \sum_{j=1}^{n_{bin}} N_{exp}(\vec{q}, \Phi_j) \sin(n\Phi_j)$$

The true numerator is then given by

$$N(\vec{q}, \Phi_j) = N_{exp}(\vec{q}) + 2 \sum_{n=1}^{n_{bin}/2} [\zeta_{n,m} N_{c,n}^{exp}(\vec{q}) \cos(n\Phi_j) + N_{s,n}^{exp}(\vec{q}) \sin(n\Phi_j)]$$

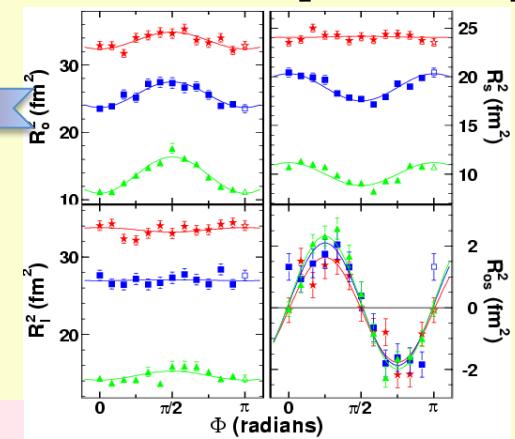
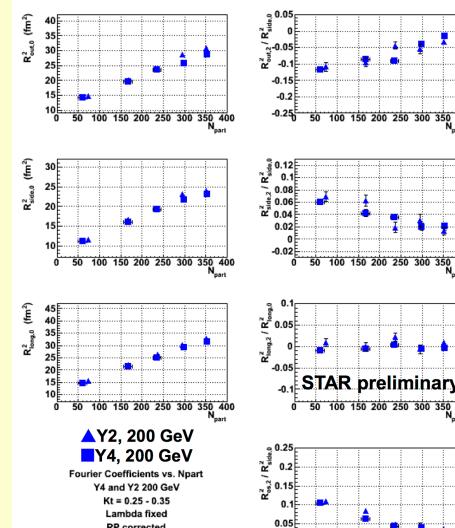
where the correction term is

$$\zeta_{n,m} = \frac{n\Delta/2}{\sin(n\Delta/2)} \left(\frac{1}{\cos(n(\Psi_m - \Psi_R))} - 1 \right)$$

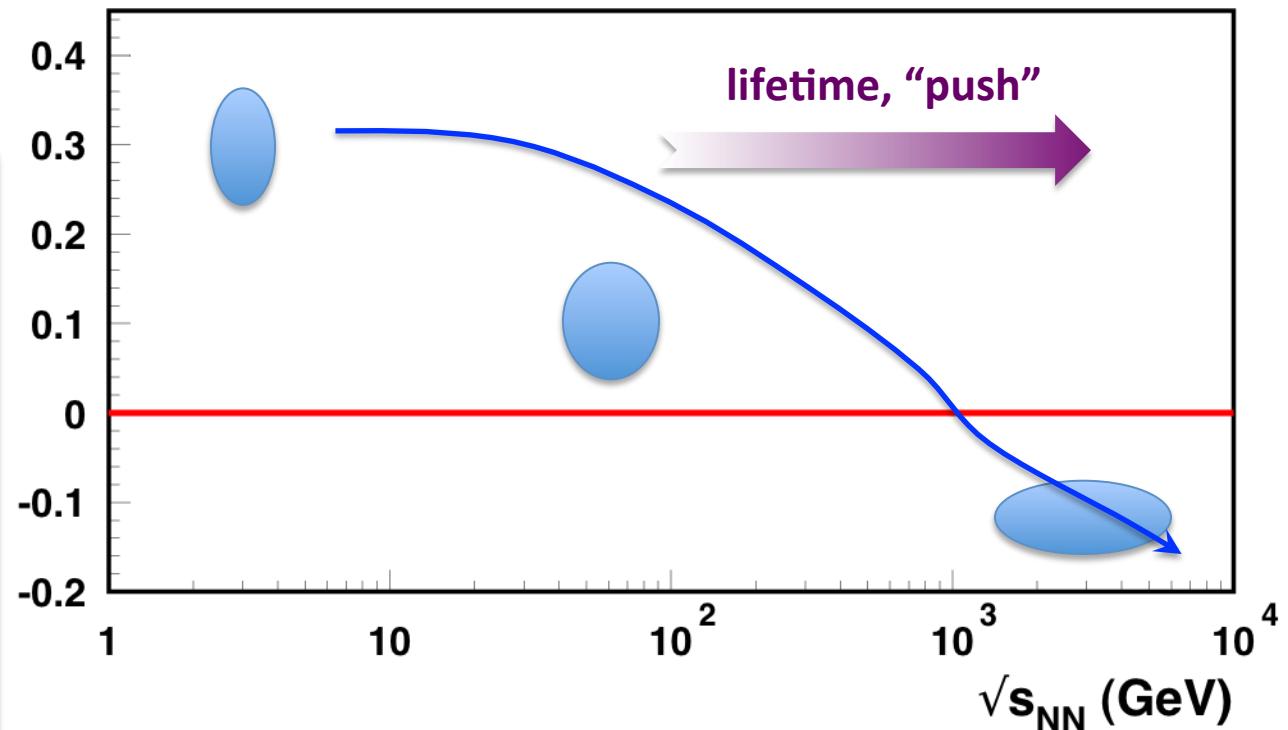
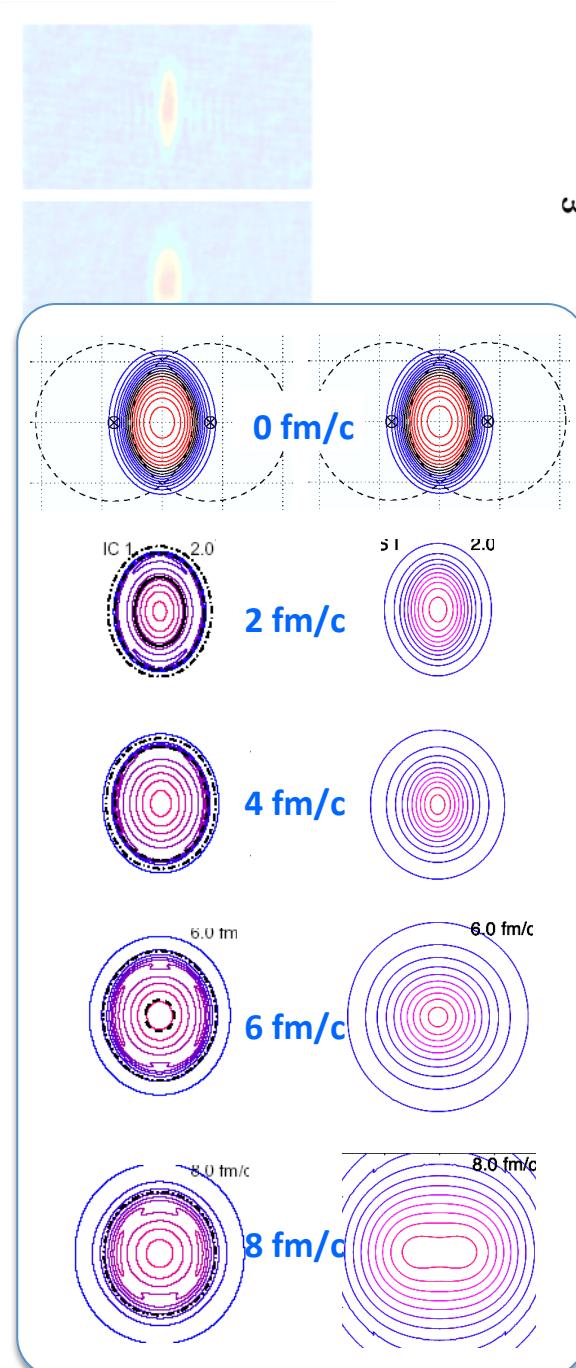


4 (8) sets of 4 (6) radii

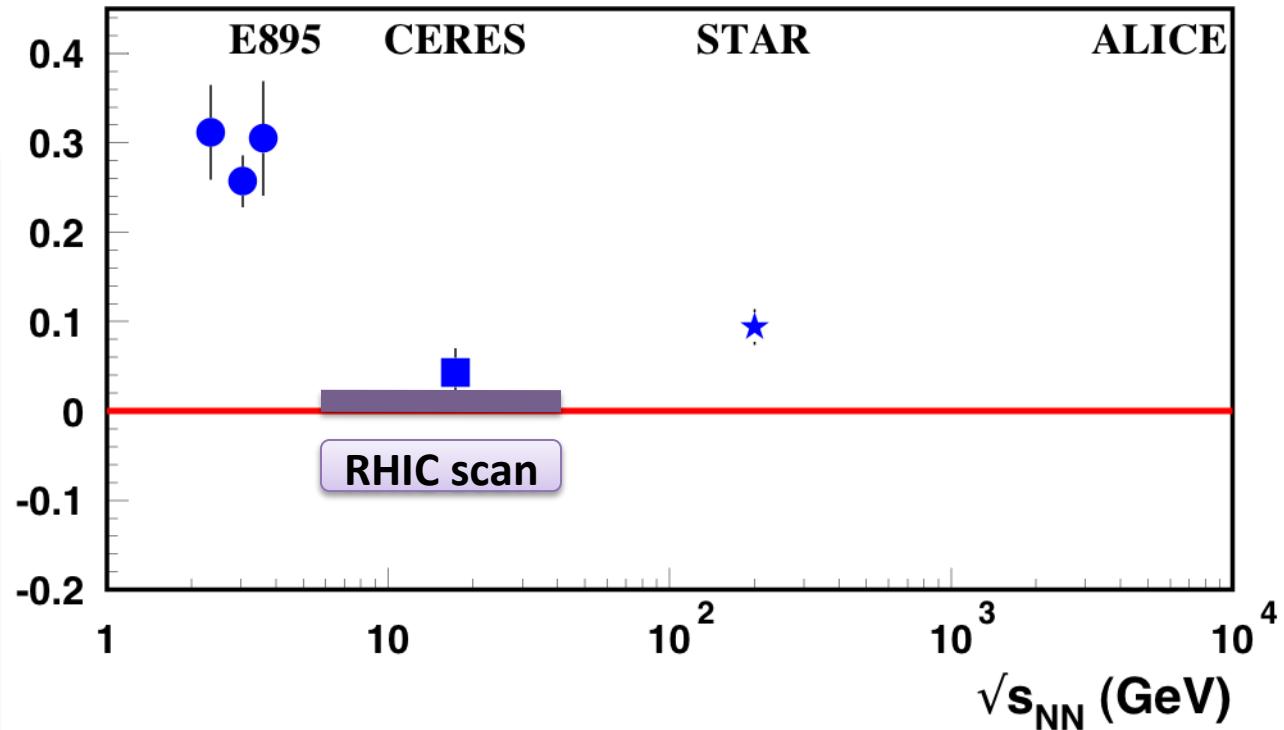
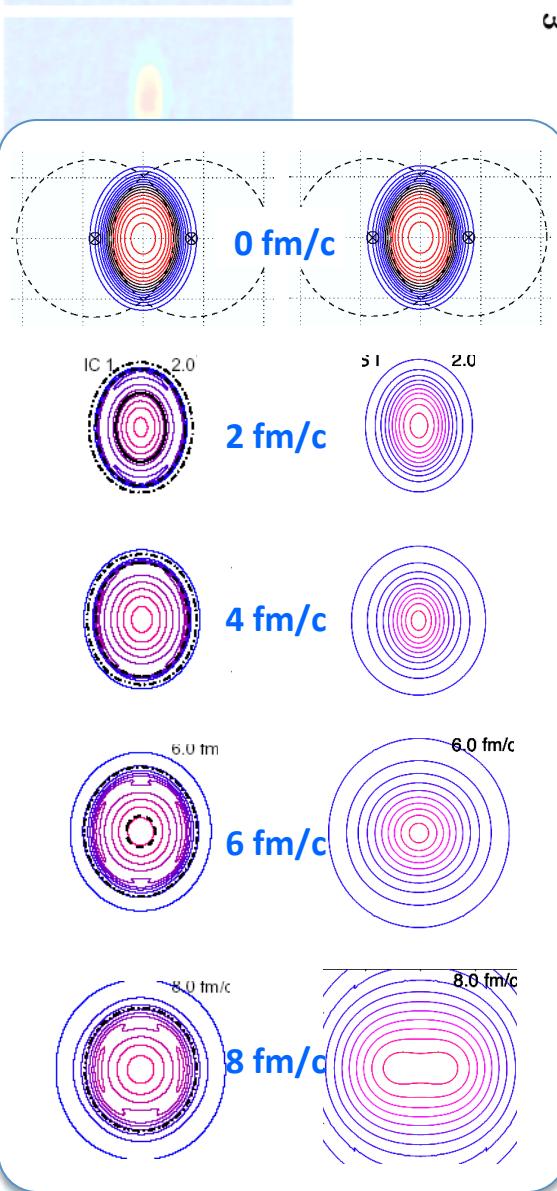
$$C^{fit}(\vec{q}) = 1 + \lambda \exp \left[- \sum_{i,j=o,s,l} q_i q_j R_{i,j}^2 \right]$$



Generic expectation



An excitation function begging for more

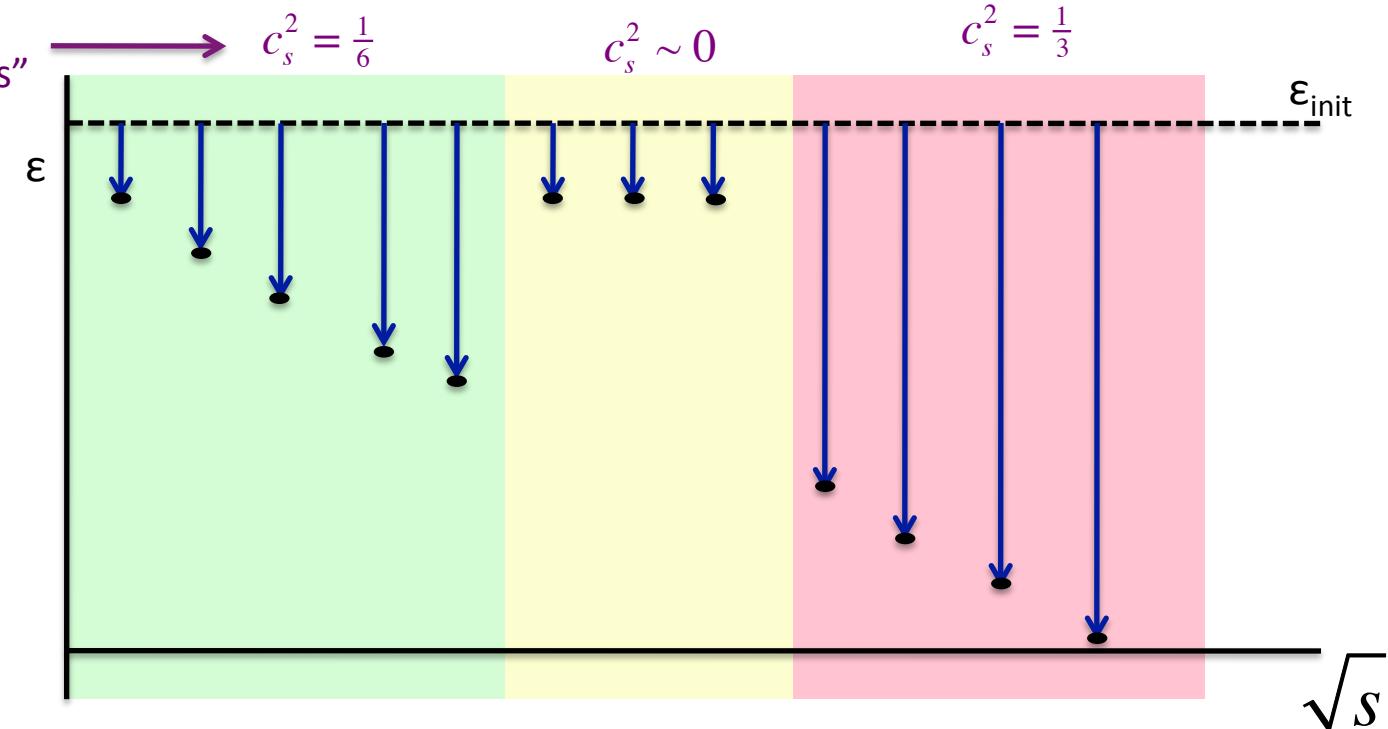


- non-monotonic excitation function of bulk observable?
 - interesting in proposed scan region
 - **but:** tilt issue – need 1st-order plane in scan!!

A pleasant daydream

Focus on effect of EoS. Keep $\varepsilon_{\text{init}}$ and effective lifetime fixed

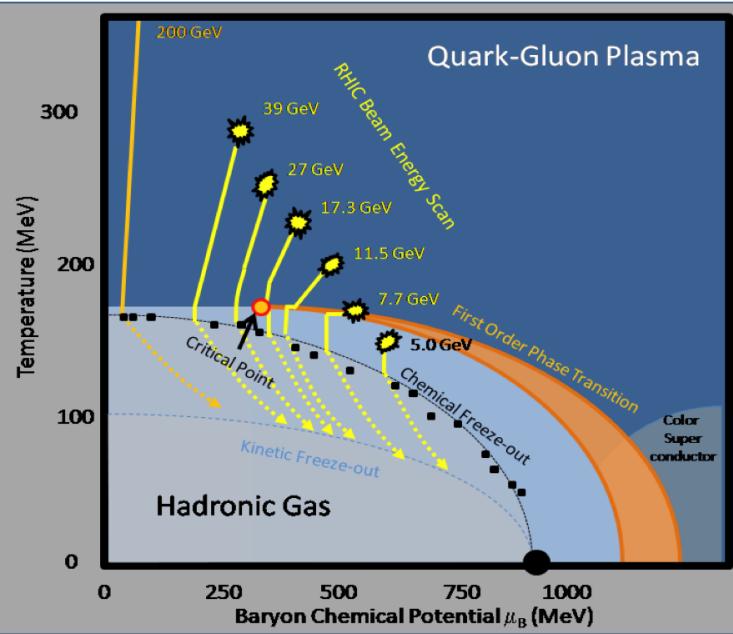
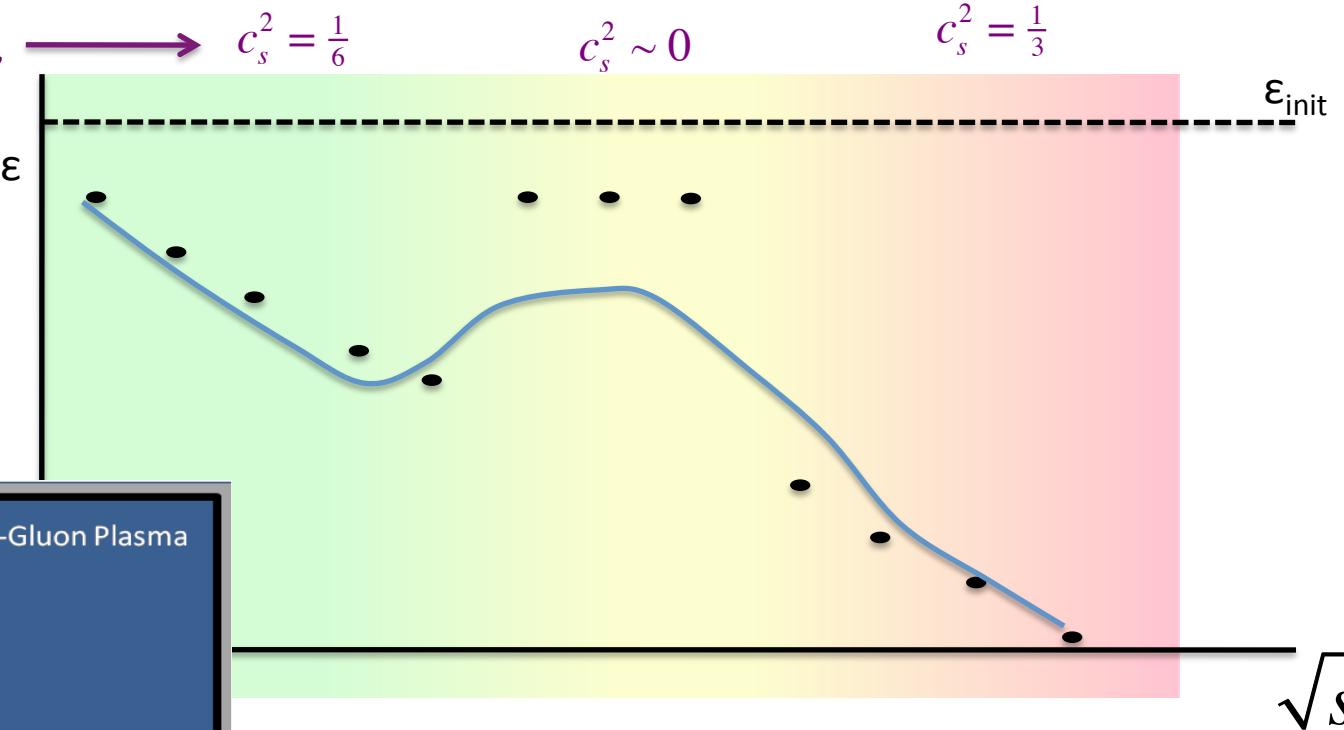
sound speed
early "stiffness"



A pleasant daydream

Focus on effect of EoS. Keep $\varepsilon_{\text{init}}$ and effective lifetime fixed

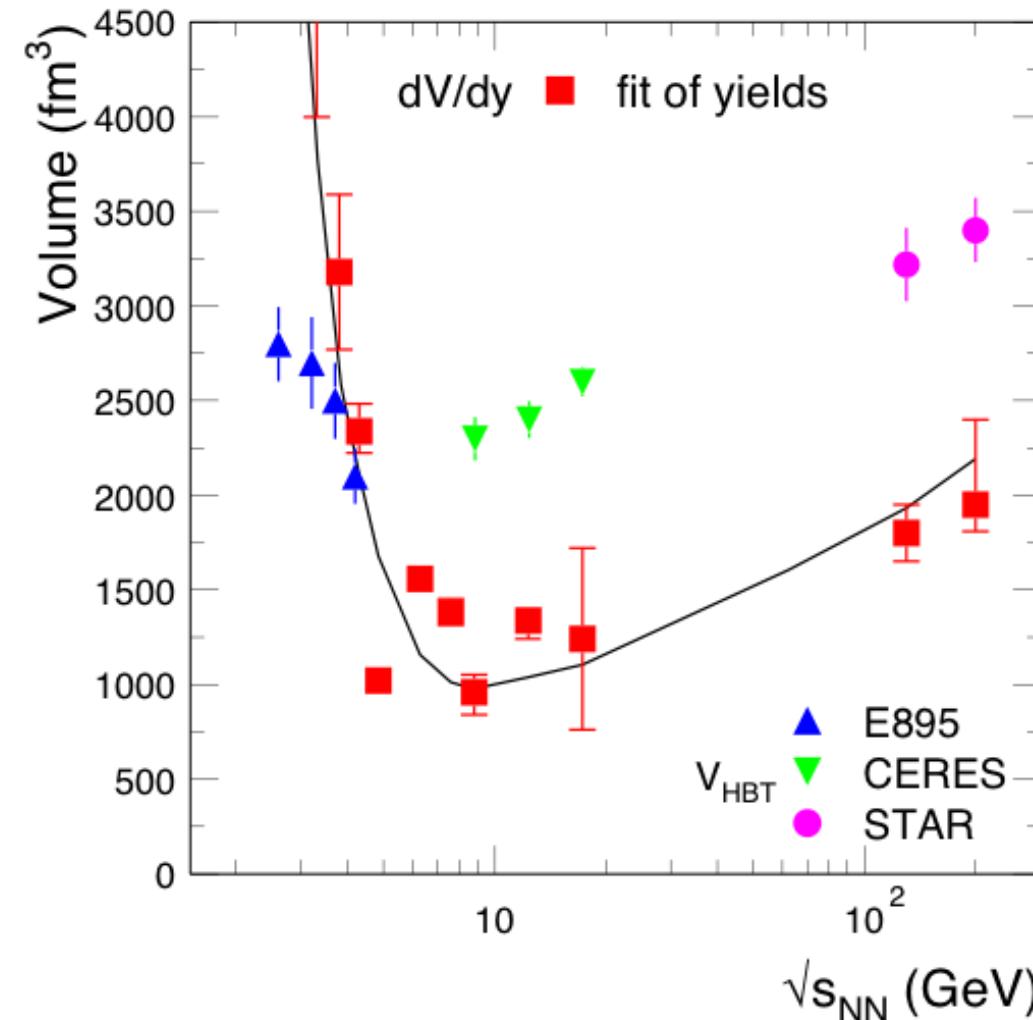
sound speed
early "stiffness"



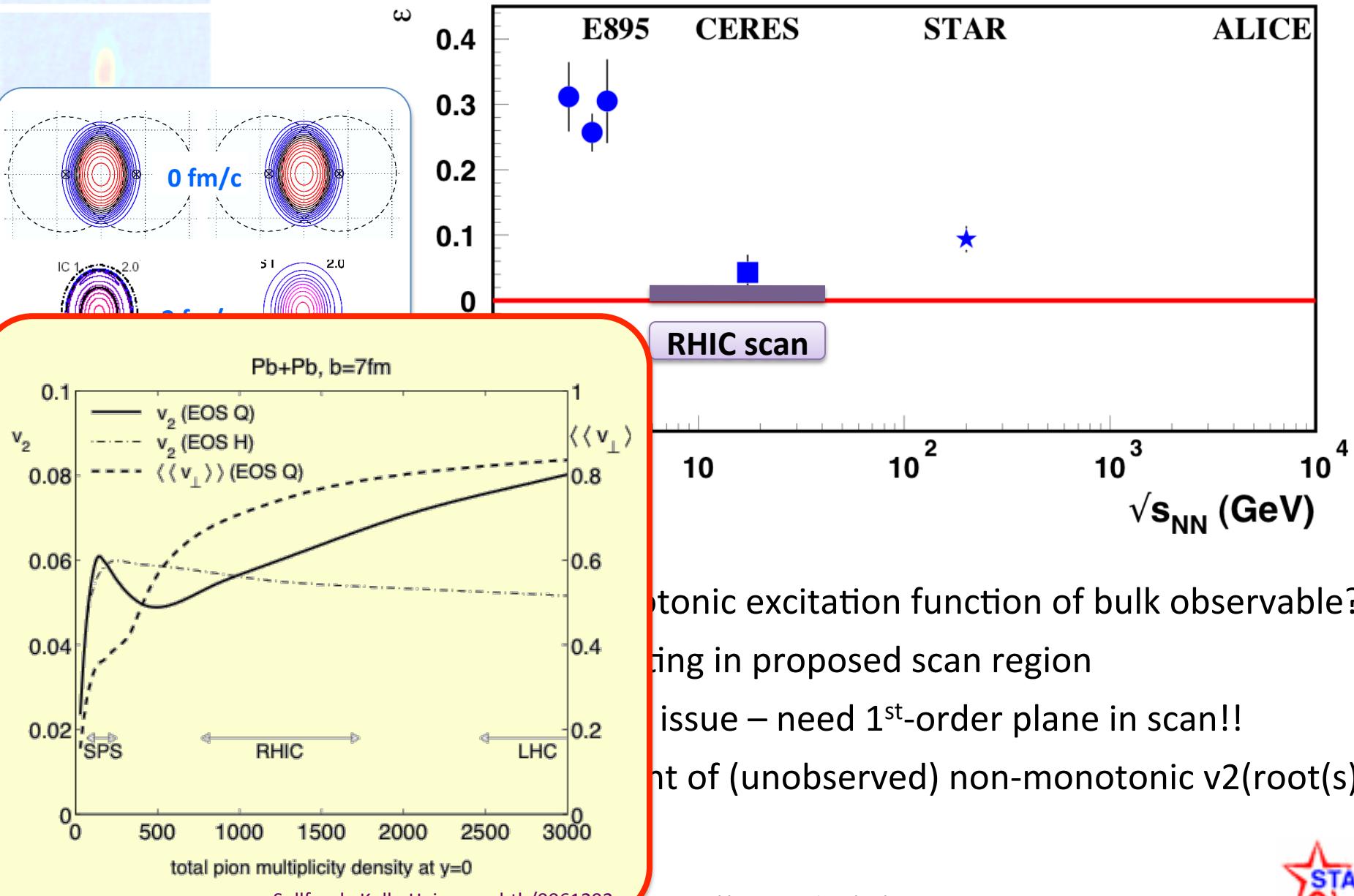
N.B.: seek $c_s^2 \approx 0$ at $\mu_B \neq 0$

Related?

Andronic arXiv:0911.4806

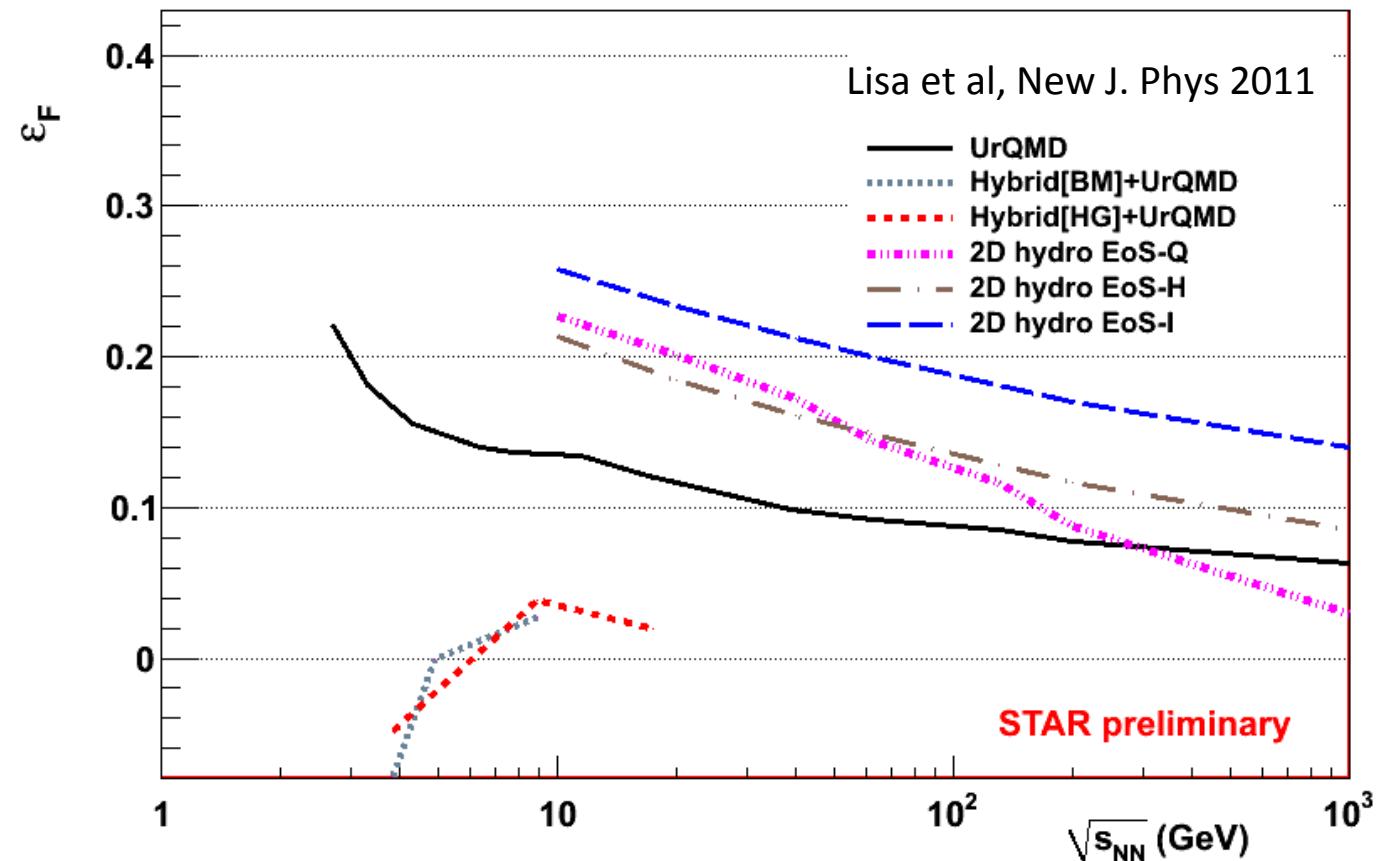


An excitation function begging for more



transport predictions (or “untuned postdictions”)

Excitation function for freeze out eccentricity, ε_F



naive expectation: absent something special, monotonic decrease

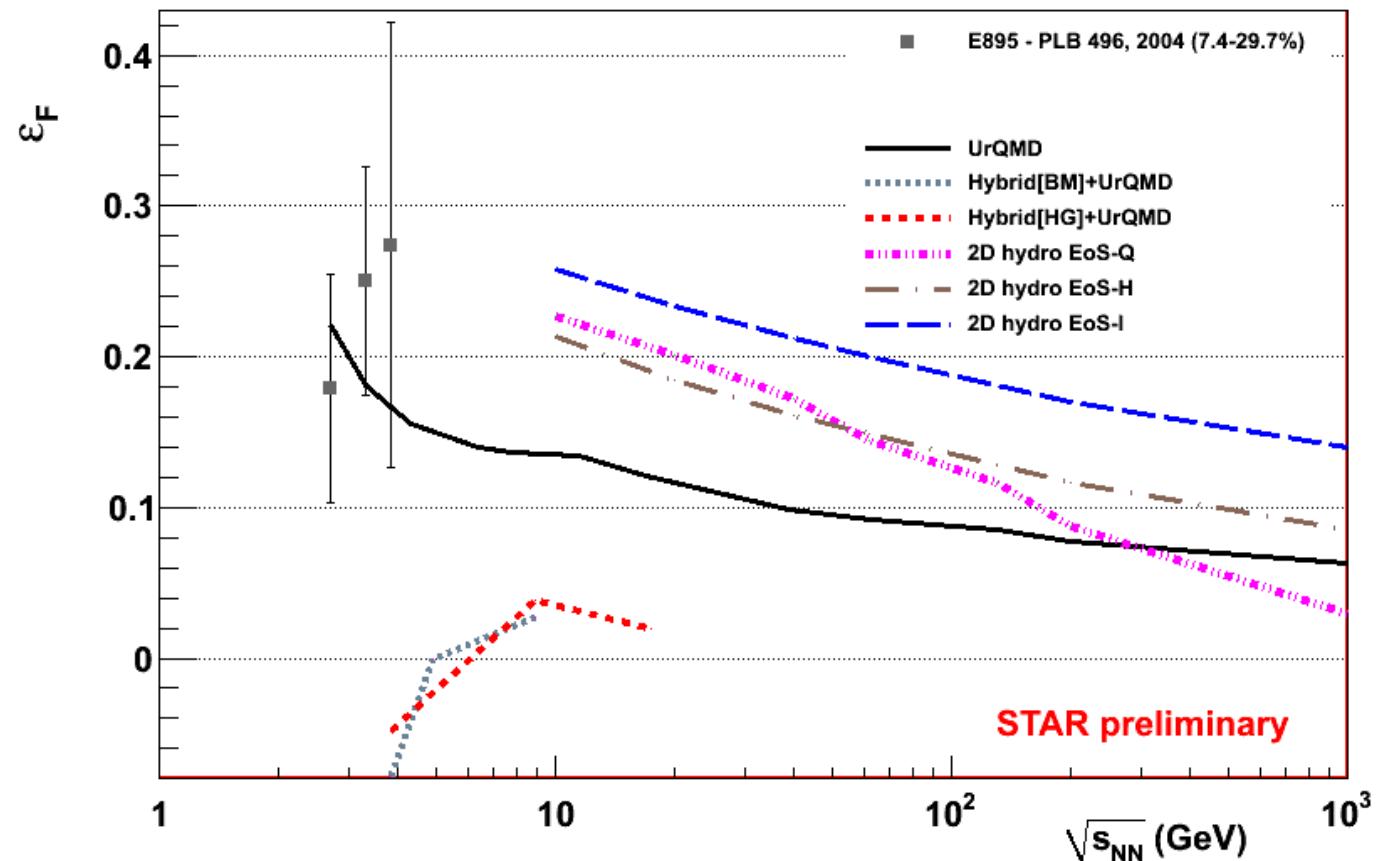
- higher energy → more pressure → evolve to smaller ε_F
- higher energy → longer lifetime → evolve to smaller ε_F

(hybrid models – special case)

certainly no minimum

10+ years of asHBT systematics

Excitation function for freeze-out eccentricity, ε_F

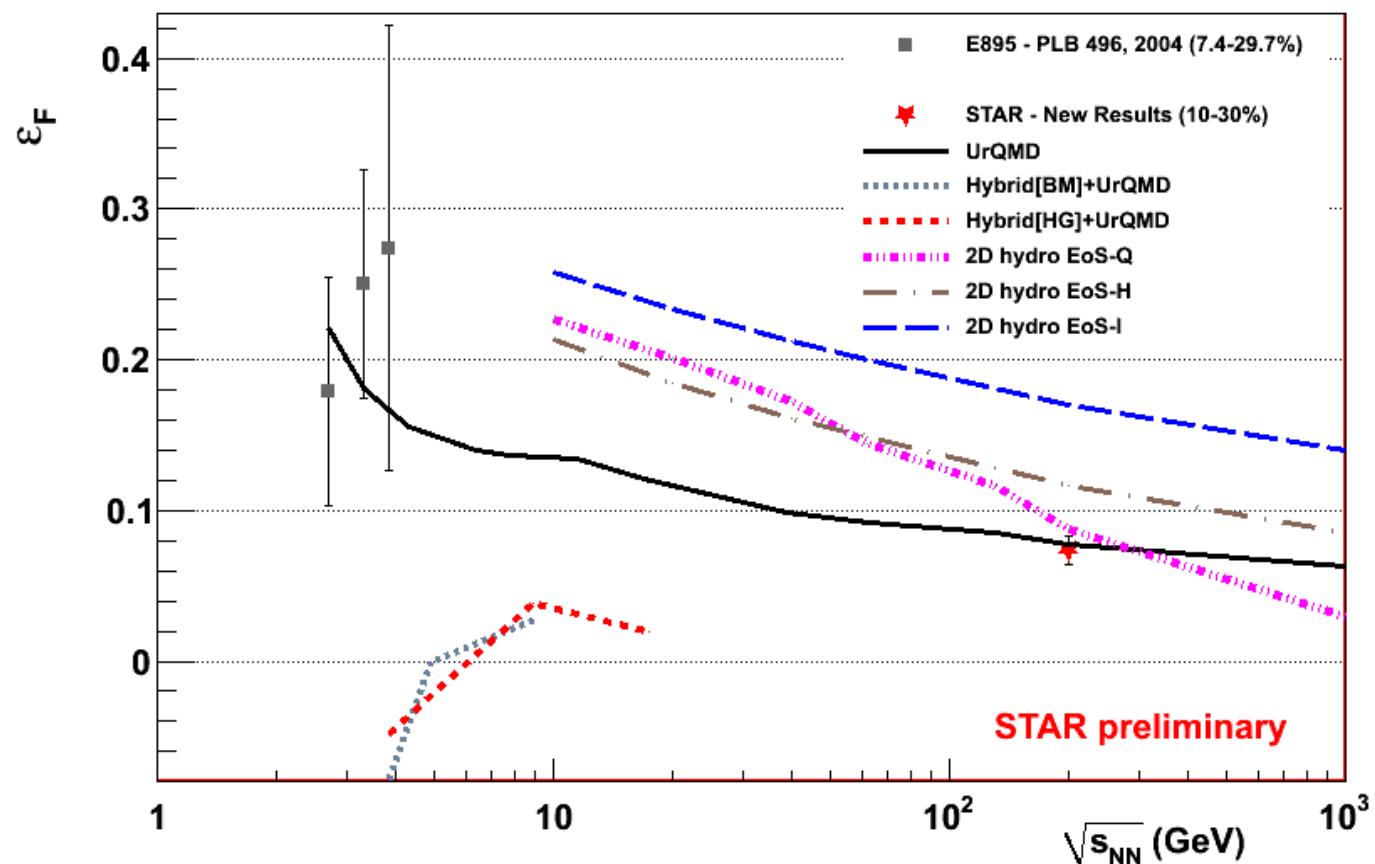


2000 : E895/AGS
PLB496 1 (2000)

2004: STAR/RHIC
200 GeV
PRL93 012301 (2004)

10+ years of asHBT systematics

Excitation function for freeze-out eccentricity, ε_F



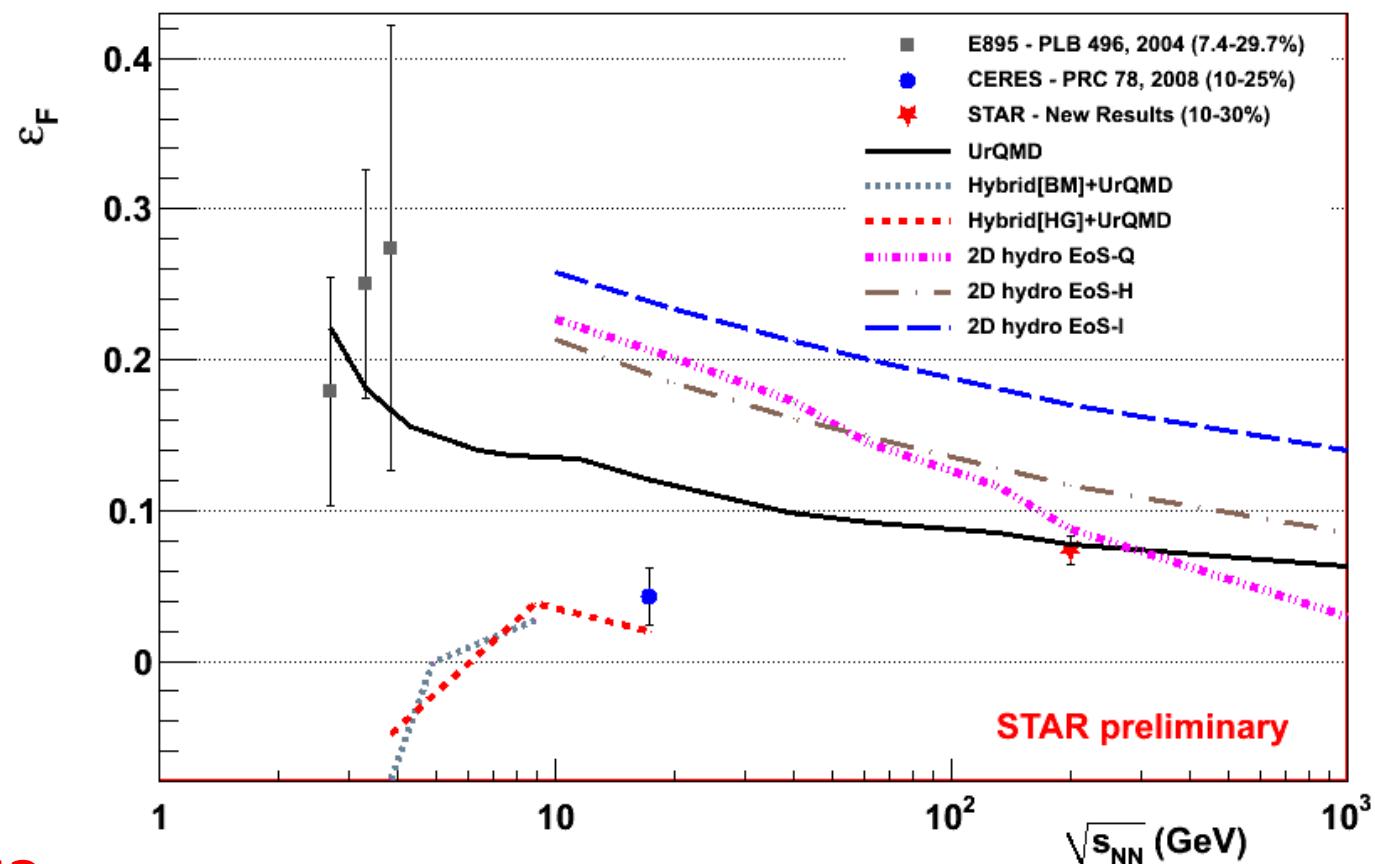
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2008: CERES/SPS
PRC78 064901 (2008)

10+ years of asHBT systematics

Excitation function for freeze-out eccentricity, ε_F



!? Something special?

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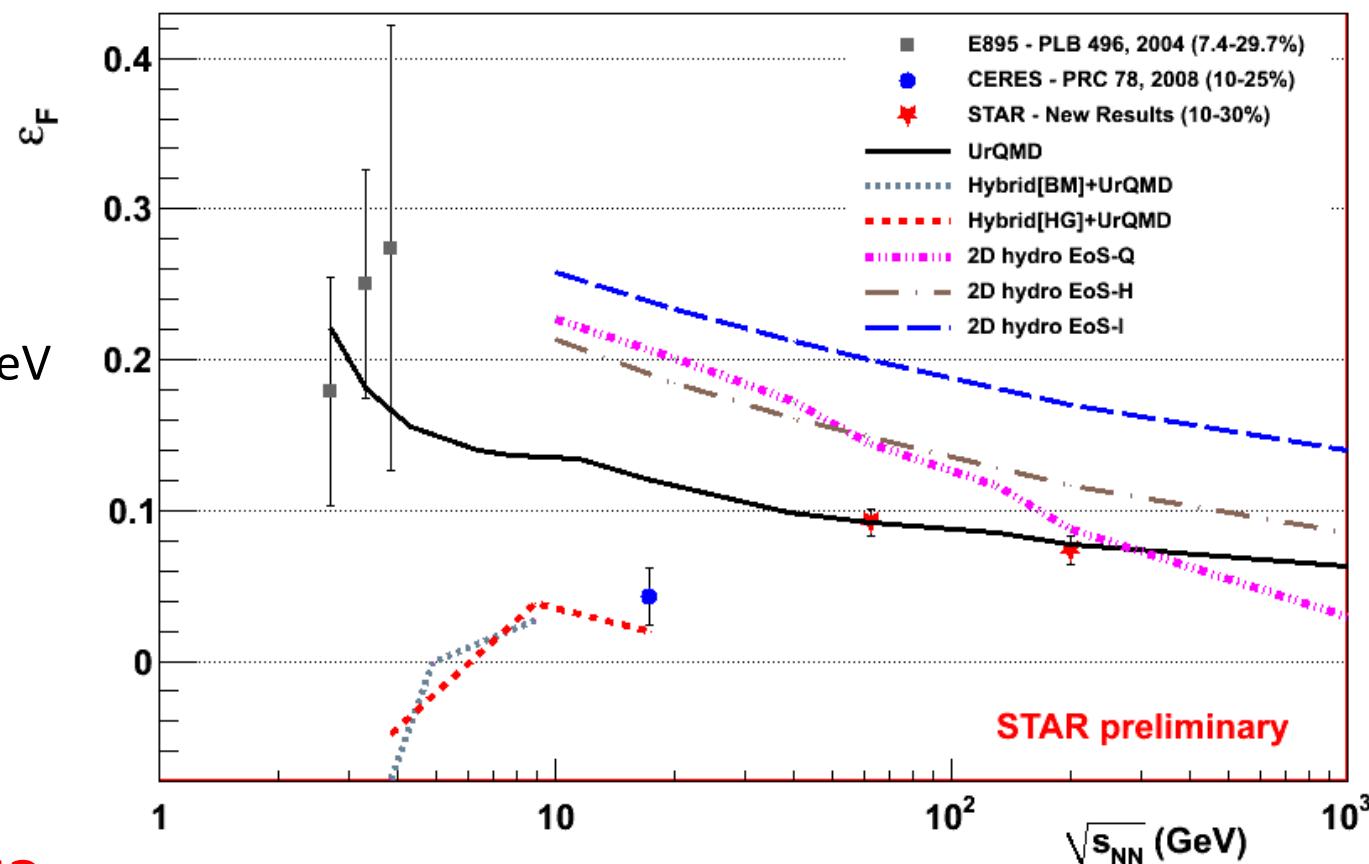
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2010 (WPCF Kiev):
STAR/RHIC 62.4 GeV

10+ years of asHBT systematics

Excitation function for freeze-out eccentricity, ε_F



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!? A real minimum? – speculation of P.T. (Lisa et al, New J. Phys 2011)

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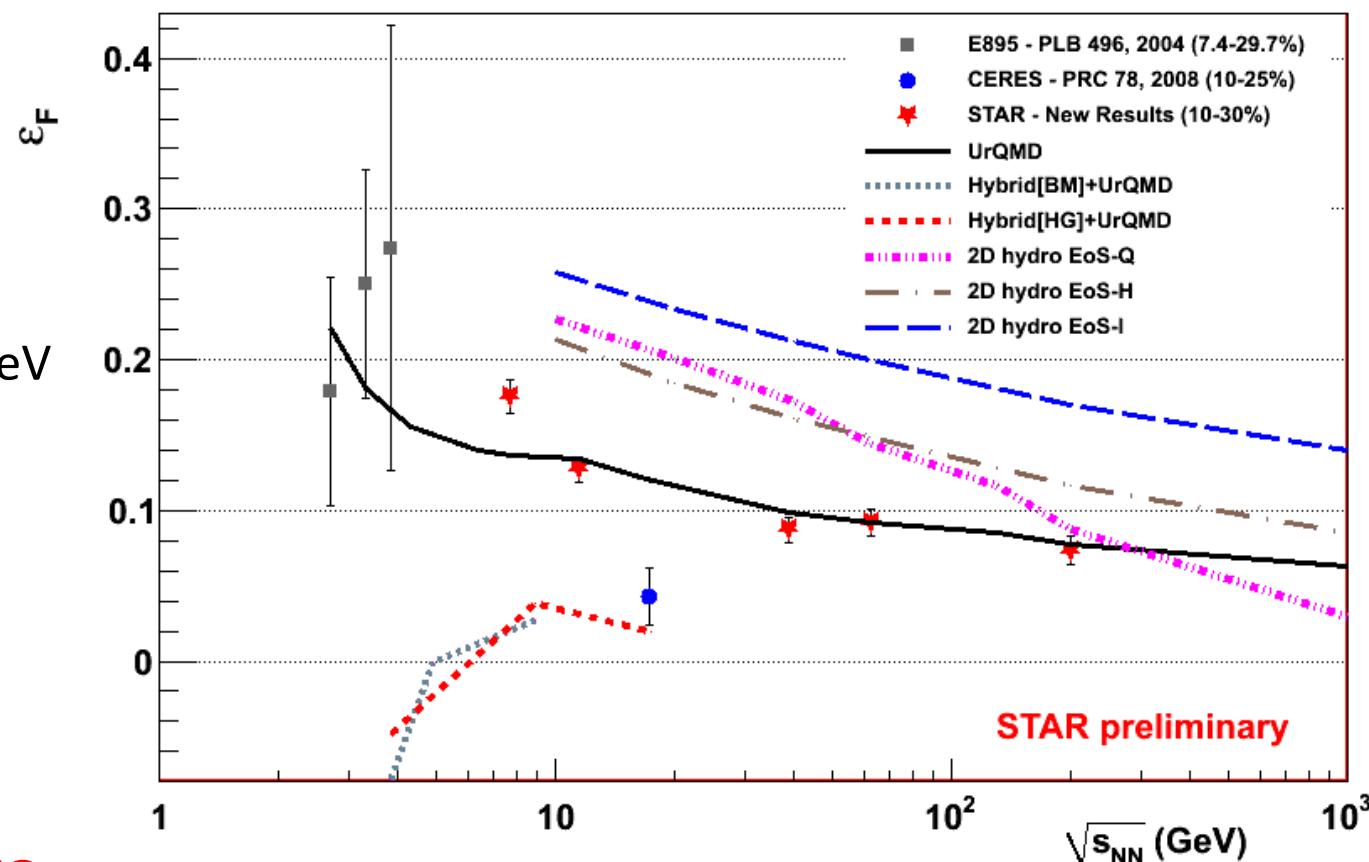
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2011 (QM Annecy):
STAR/RHIC
7.7, 11.5, 39 GeV
arXiv:1107.1527

10+ years of asHBT systematics

Excitation function for freeze-out eccentricity, ε_F



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!!!? A real **sharp** minimum at the “special” kink/horn/step energy?

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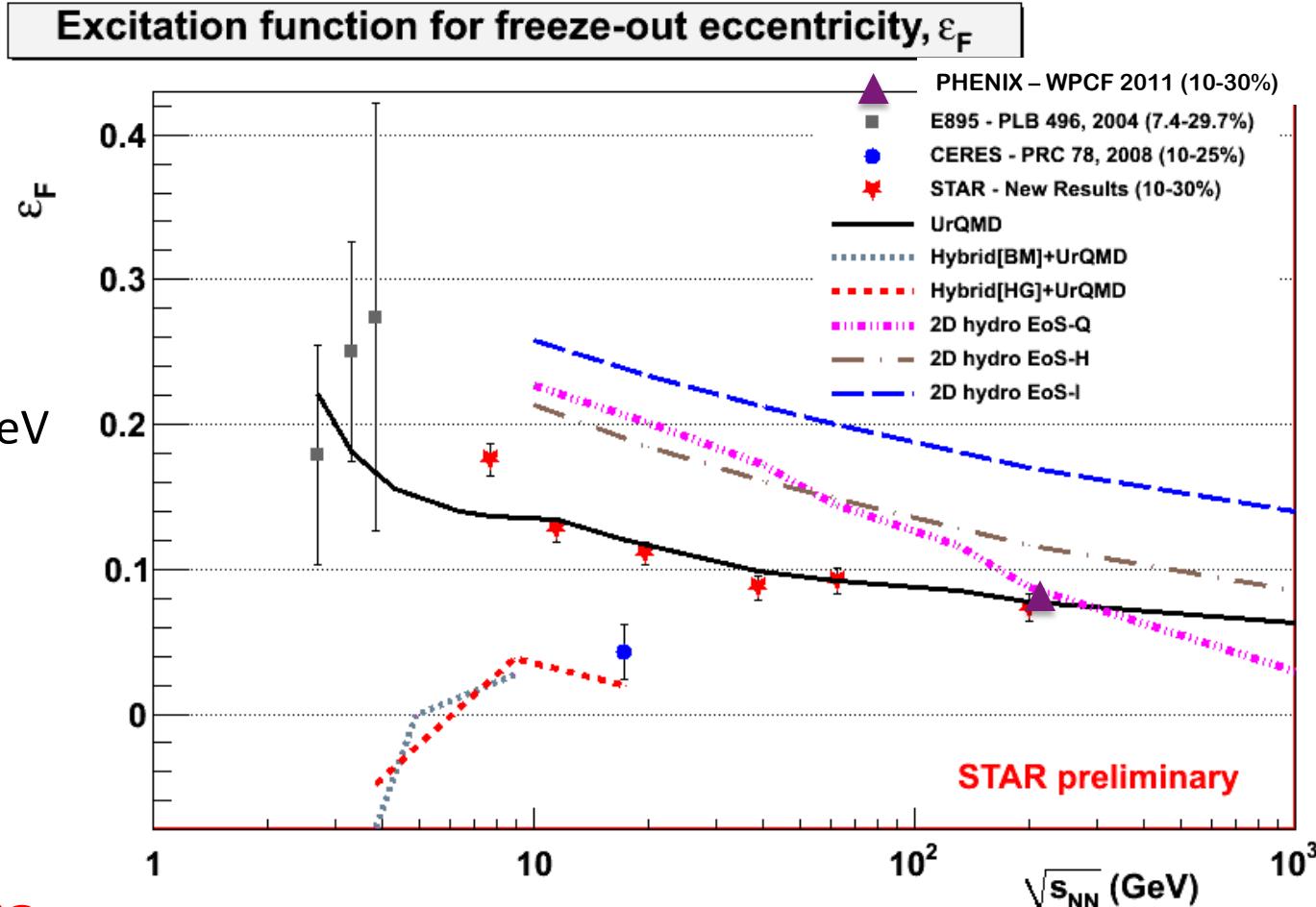
2011 (QM Annecy):
STAR/RHIC
7.7, 11.5, 39 GeV
arXiv:1107.1527

2011 (WPCF Tokyo)
STAR/RHIC
19.6 GeV

2011 (WPCF Tokyo)
PHENIX/RHIC
200 GeV

Soon: ALICE/LHC

10+ years of asHBT systematics



!?

Something special?

!?

A real minimum? – speculation of P.T. (Lisa et al, New J. Phys 2011)

!!!?

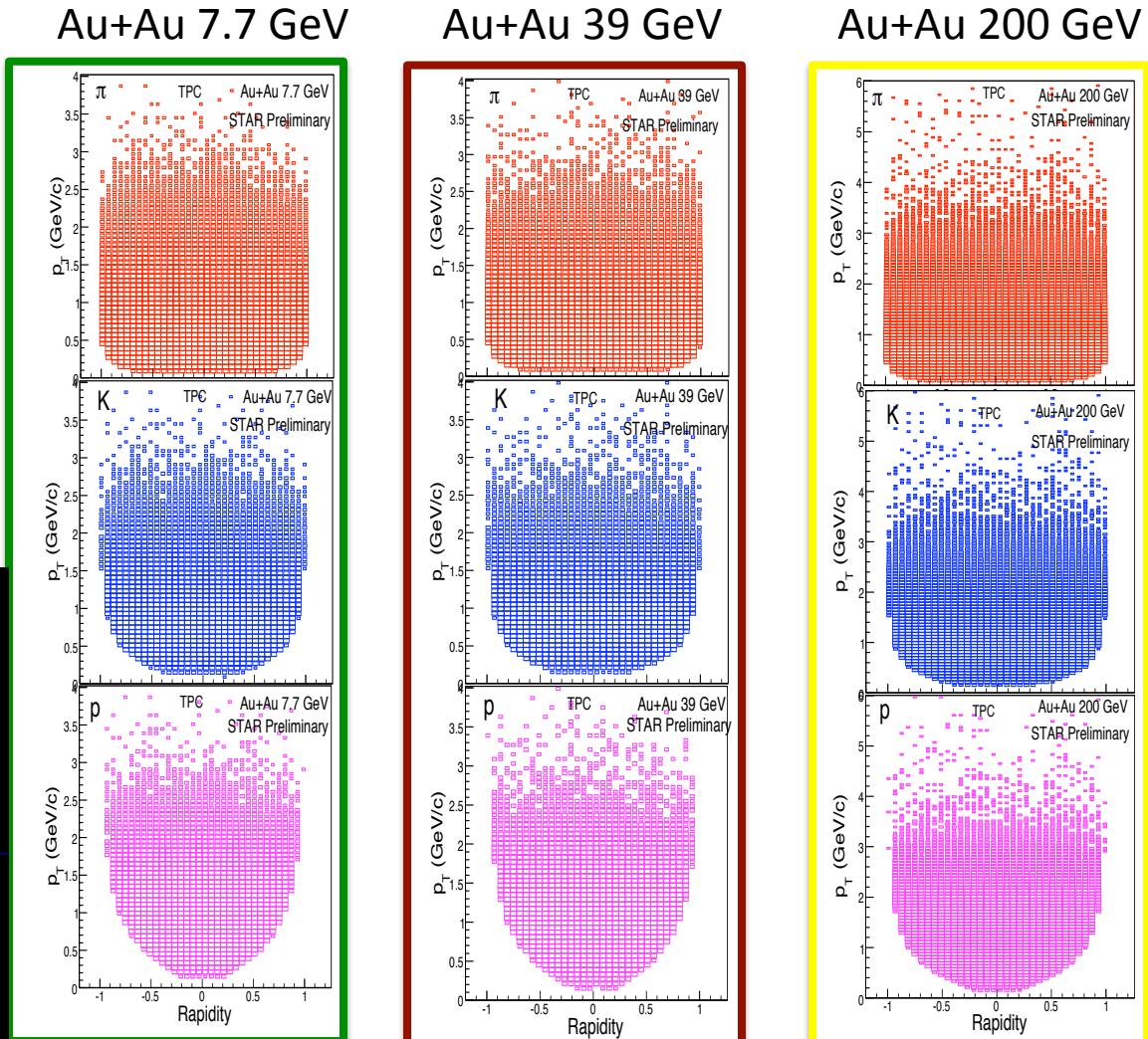
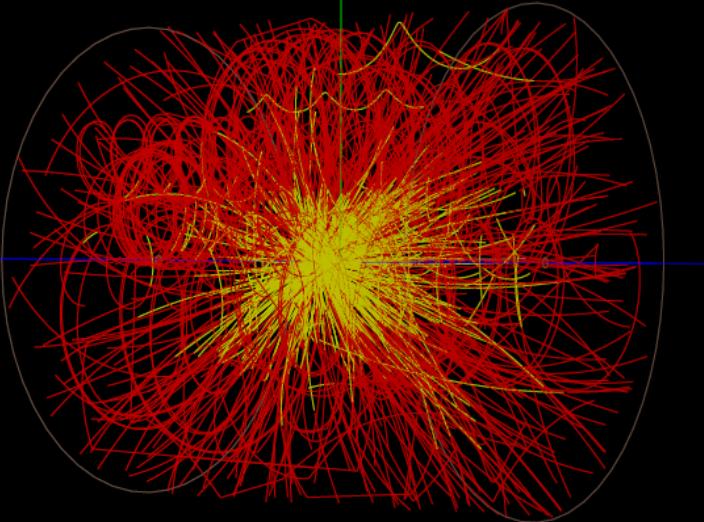
A real **sharp** minimum at the “special” kink/horn/step energy?

Uh-oh

the beauty of a single, collider detector

Identical techniques, systematics, acceptance...

BUT: cannot get complacent
Important measurement, and
cross-checks are important, if we
take data at all seriously.



can CERES and STAR be reconciled?

at this point, the energies measured are too close to reasonably expect such a difference.

What else could it be?

- different reaction-plane resolution correction technique?
- different centrality?
- different fitting parameters?
- different rapidity range?

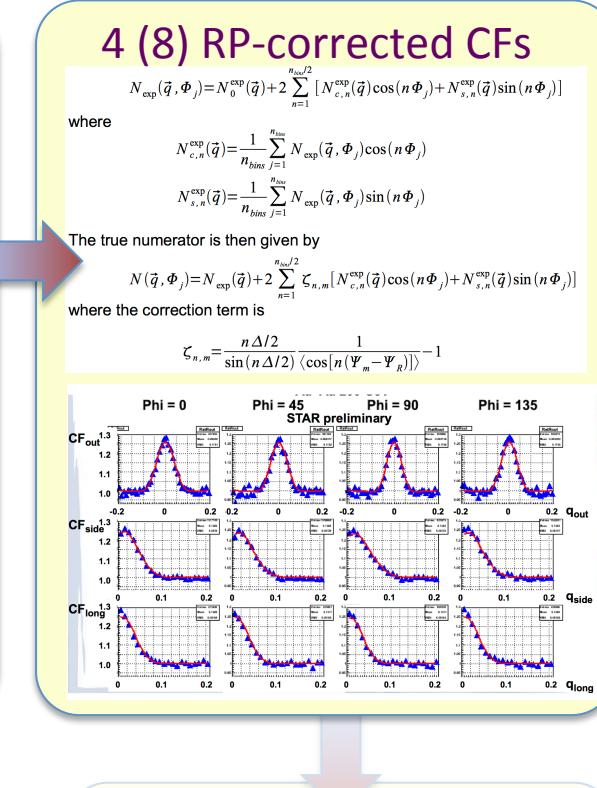
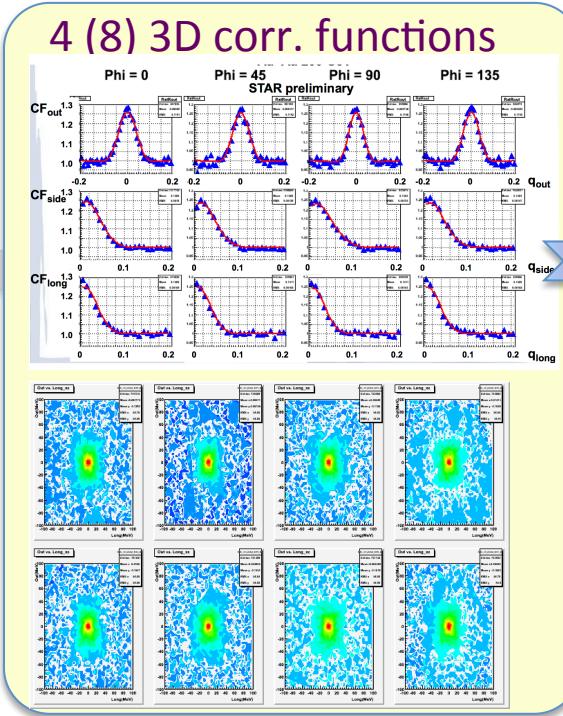
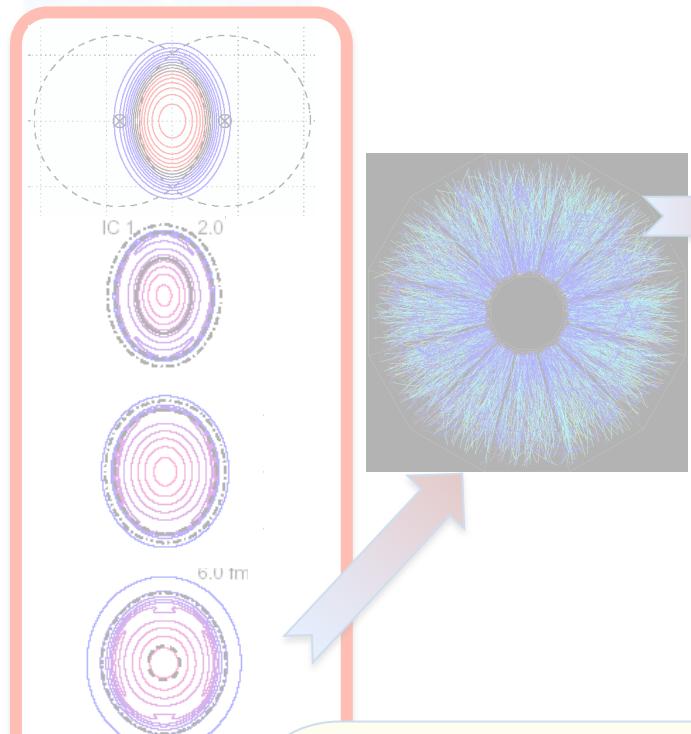
Table 2. Measurements of the anisotropic shapes from heavy ion collisions. The third column indicates which centrality bins were averaged to obtain the shape parameters of figures 6 and 7. See the text for details.

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RHIC/STAR [37]	200	$(5\text{--}10) \oplus (10\text{--}20) \oplus (20\text{--}30)$ and $(10\text{--}20) \oplus (20\text{--}30)$	$ y < 0.5$

New J. Phys. 13 065006 (2011)



Welcome to the machine



Reaction-plane resolution correction:

STAR: RP resolution correction done bin-by-bin to correlation functions

CERES: correction done to HBT radius parameters (similar to v2)

(question to CERES: was finite bin-width also accounted for? $(\Delta/2)/\sin(\Delta/2)$ ~5% effect)

1 ecc

R. Wells PhD thesis (2002): methods yielded similar results *in that case*

$$\varepsilon = 2 \frac{R_{s,0}^2}{R_s^2}$$

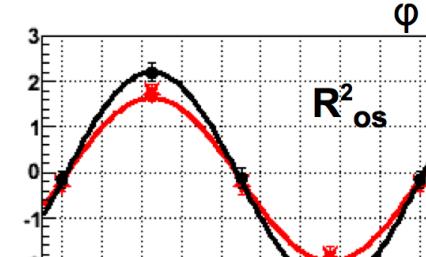
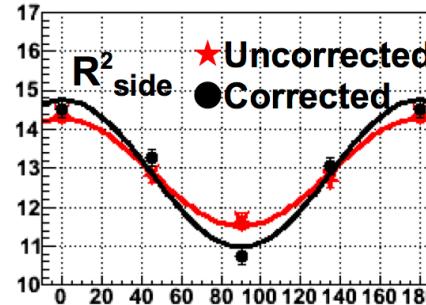
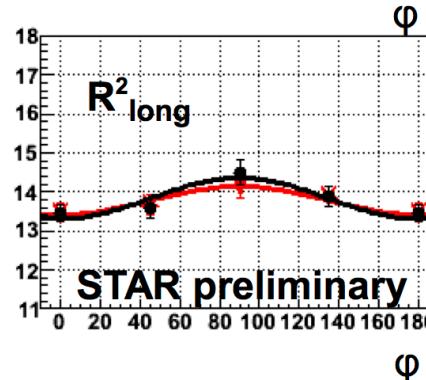
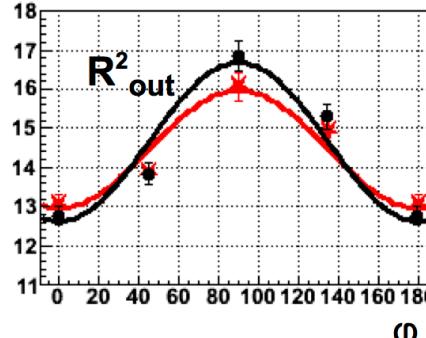


RP resolution correction

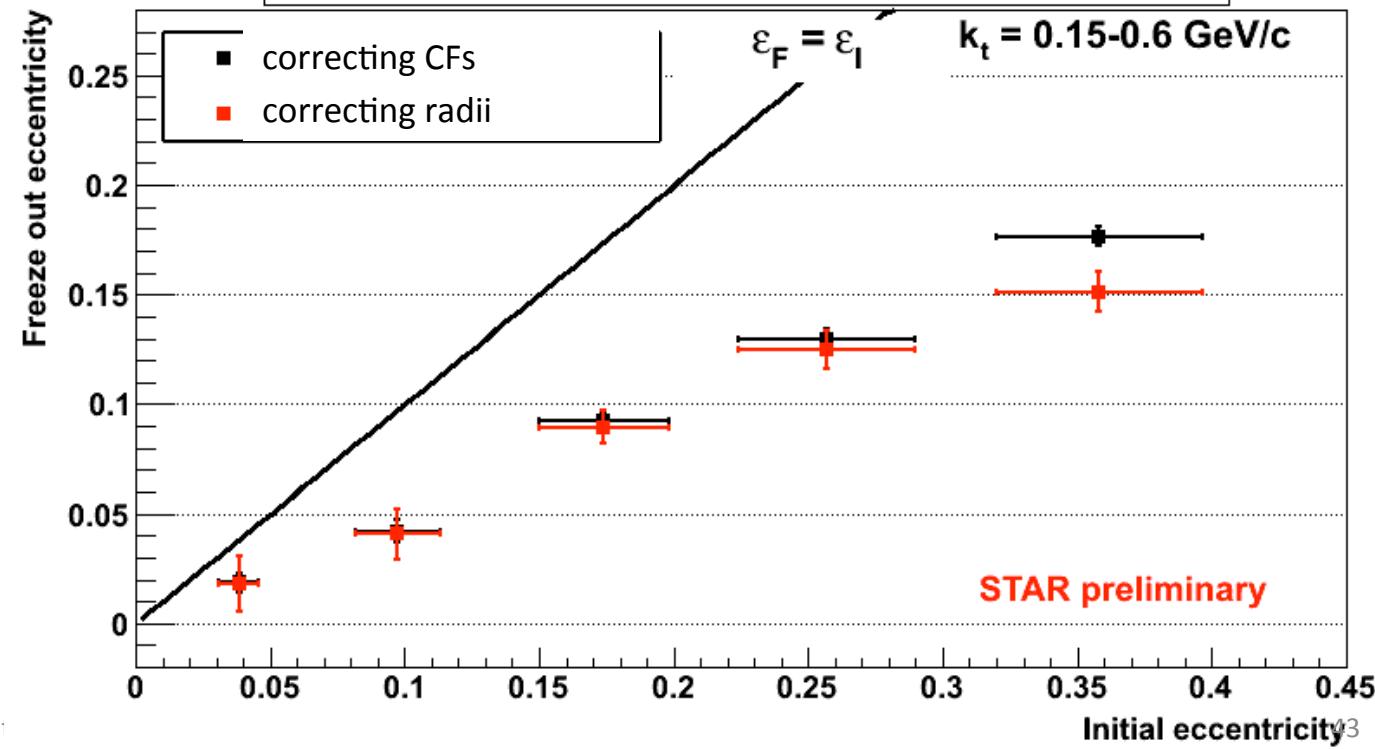
very small effect in STAR analysis

Similar at other energies

No guarantee this will be true for any other experiment, but probably not the issue



19.6 GeV ε_F vs ε_I - Comparing correction techniques



STAR preliminary

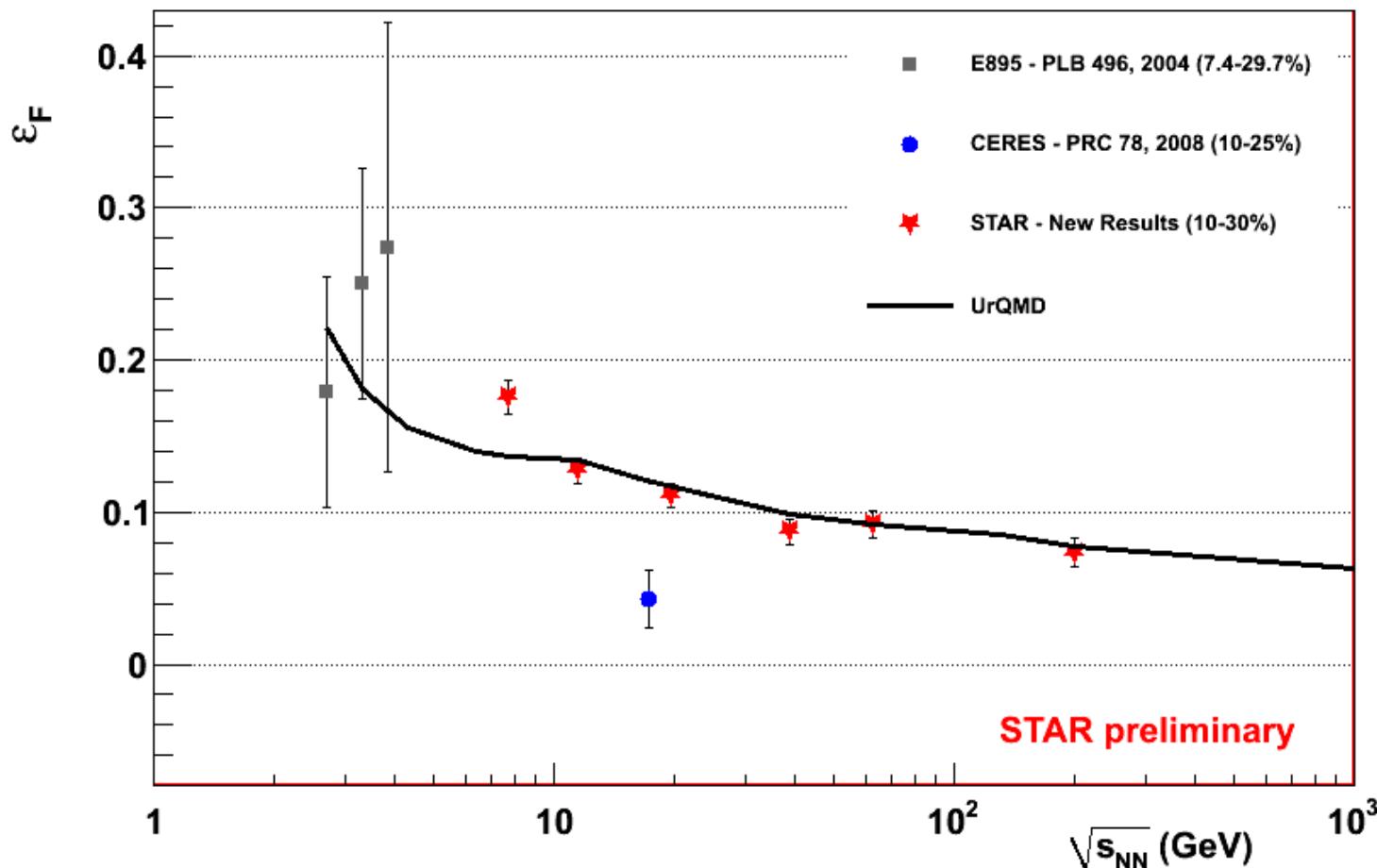


CERES

STAR

Centrality

Excitation function for freeze-out eccentricity, ε_F



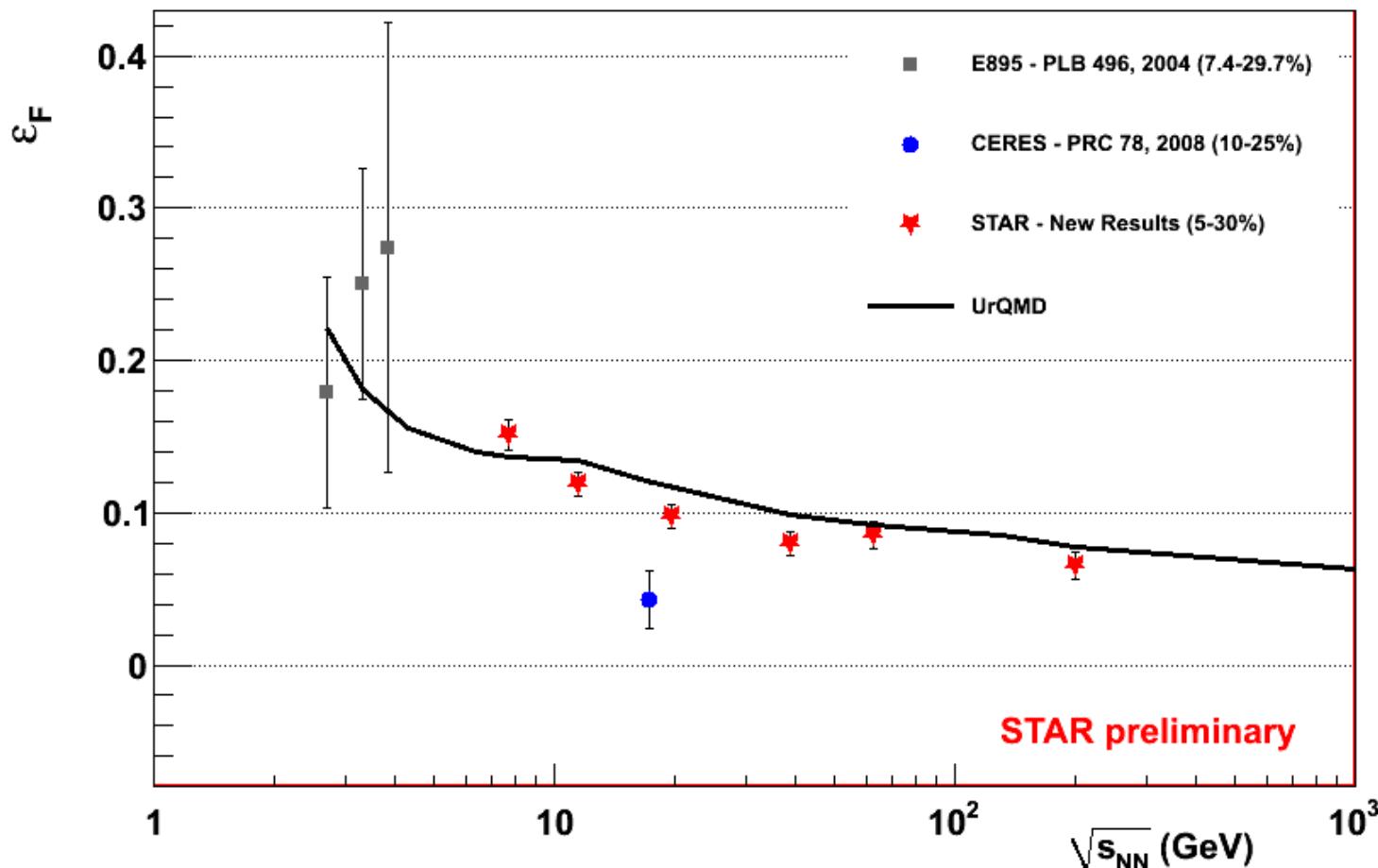


CERES

STAR

Centrality

Excitation function for freeze-out eccentricity, ε_F



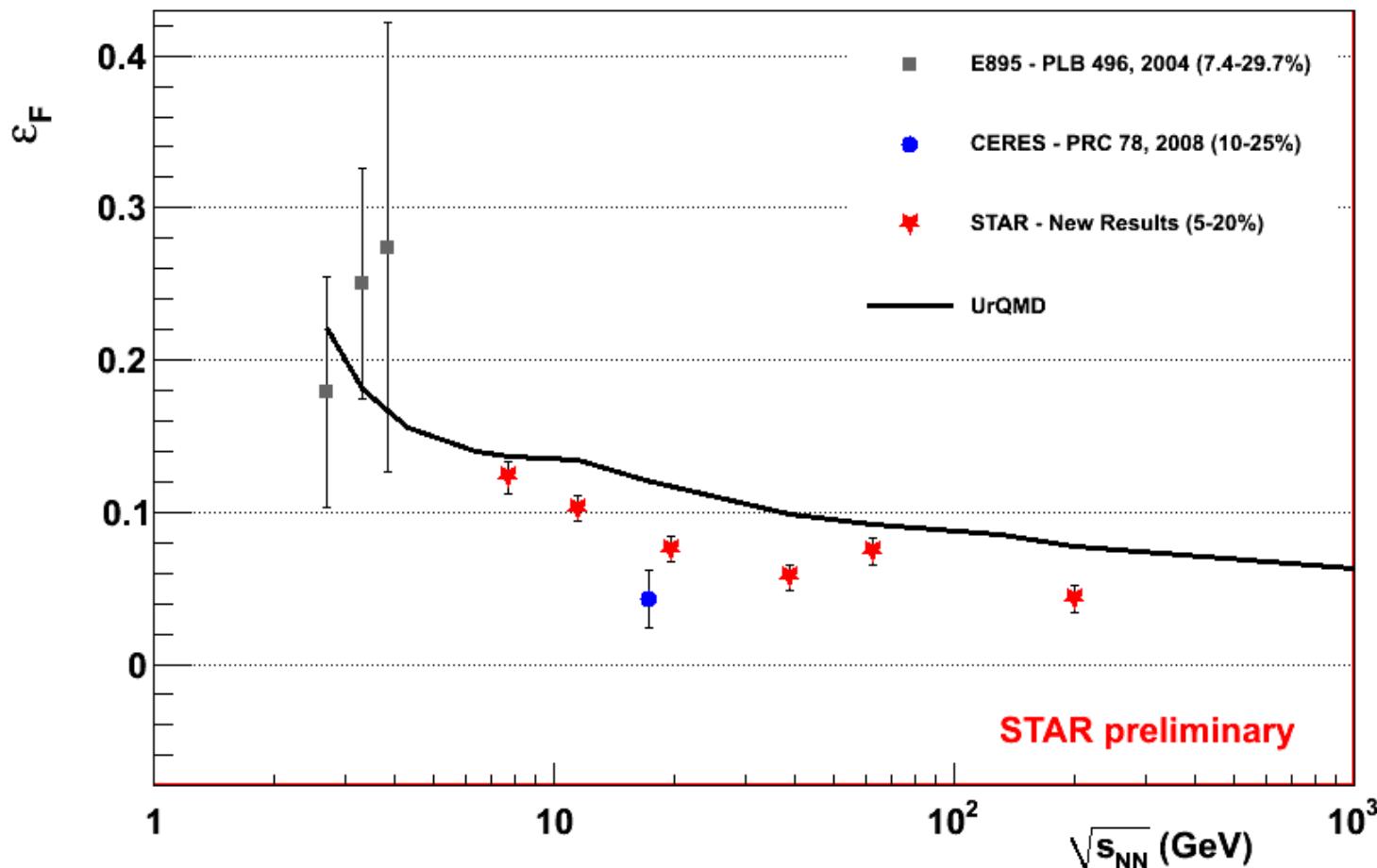


CERES

STAR

Centrality

Excitation function for freeze-out eccentricity, ε_F



STAR preliminary

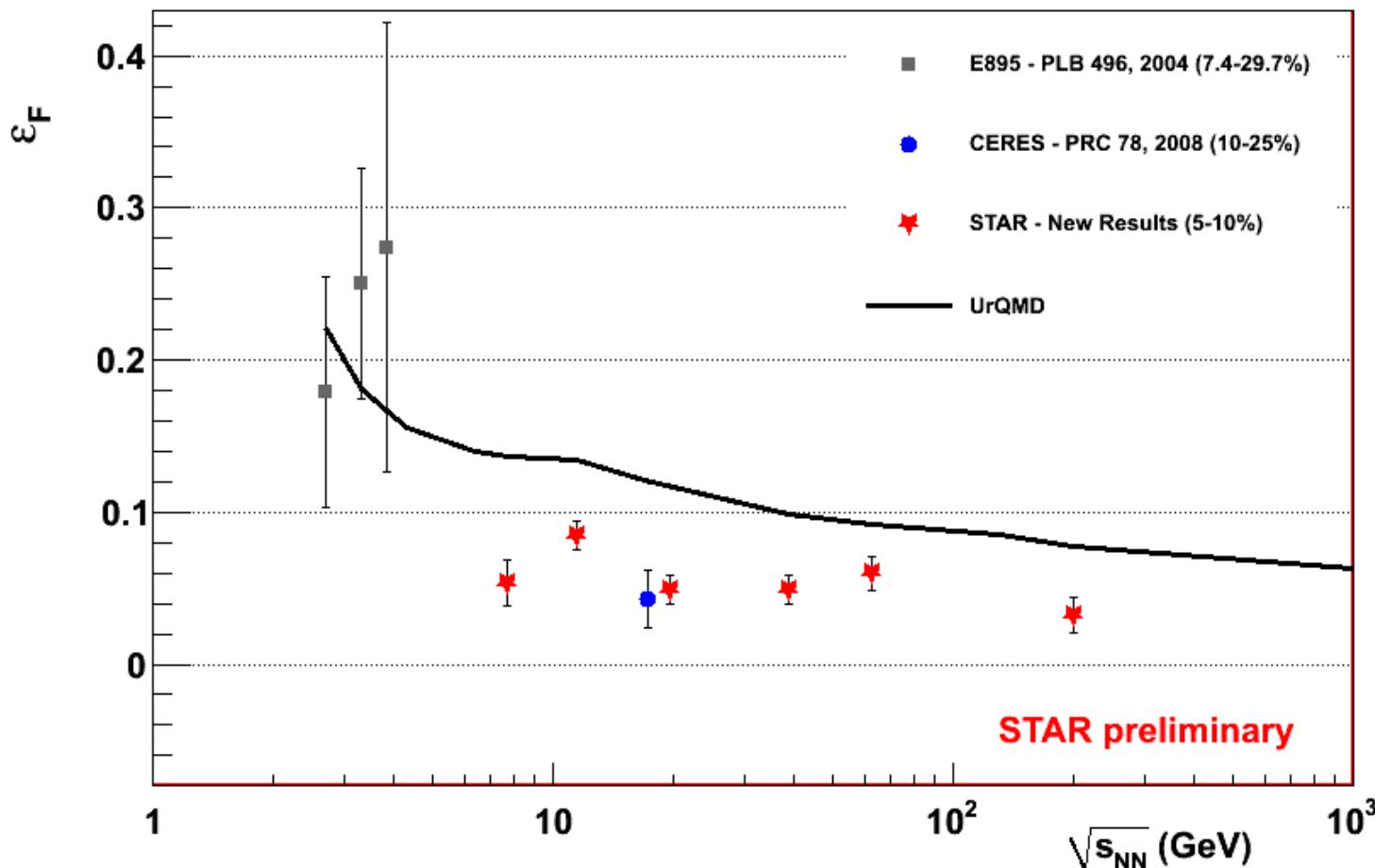


CERES

STAR

Centrality

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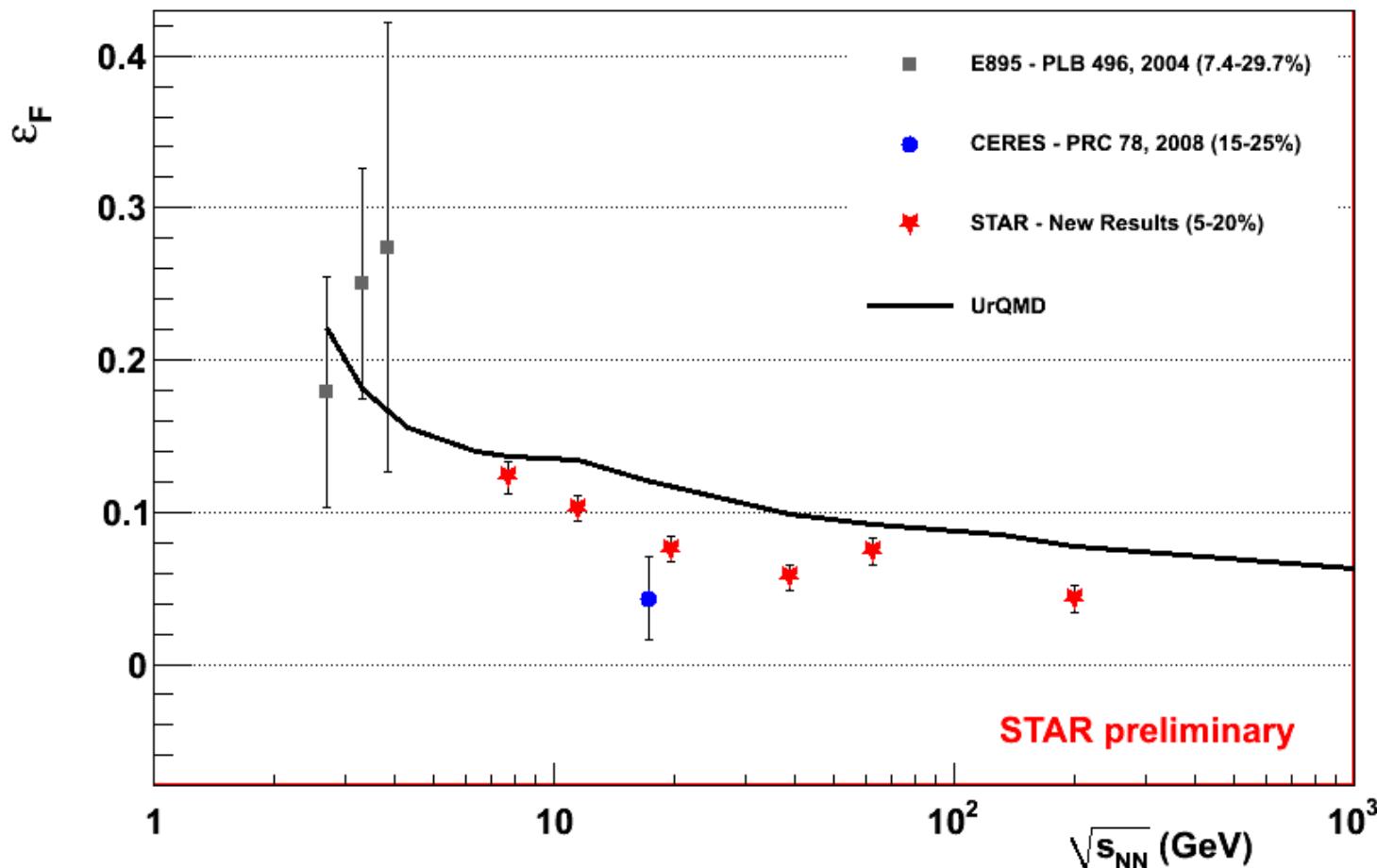


CERES

STAR

Centrality

Excitation function for freeze-out eccentricity, ε_F



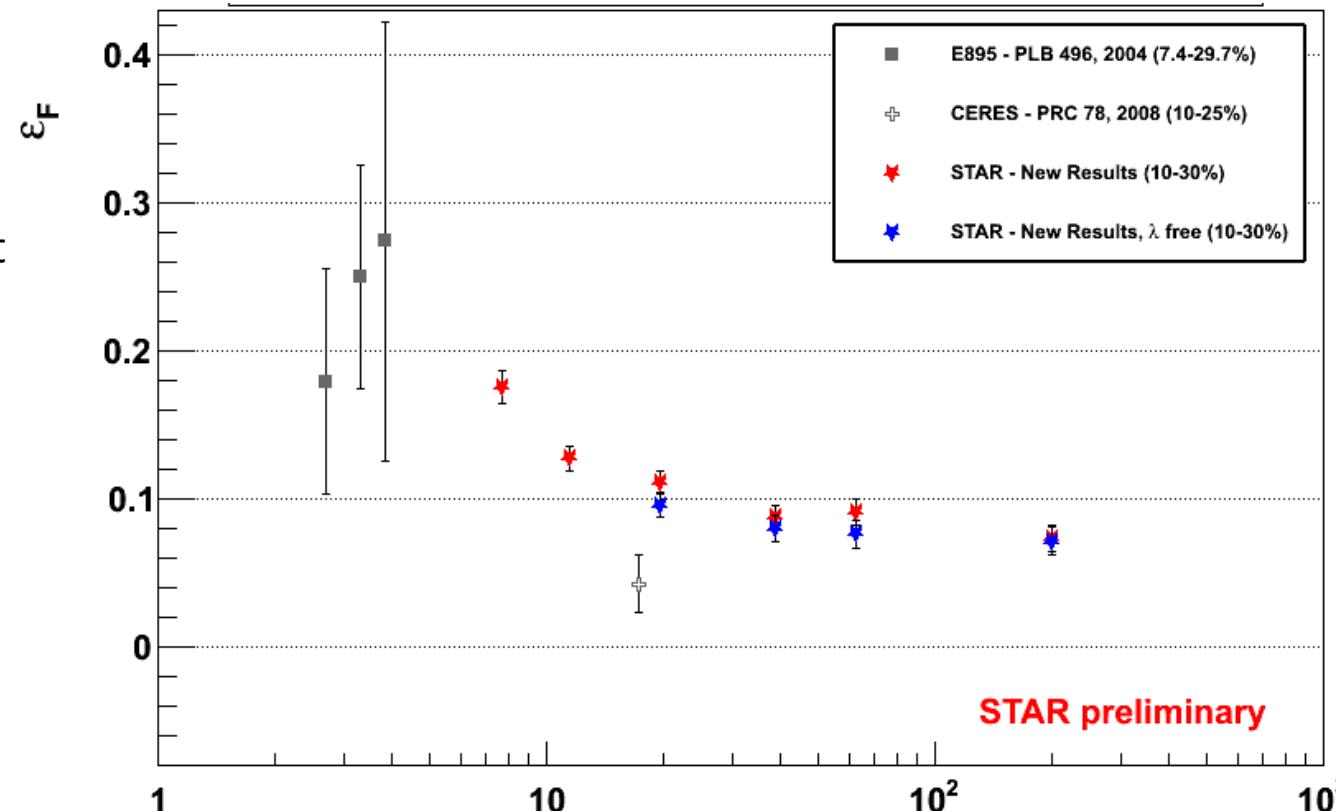
Fitting techniques

$$C(\vec{q};\phi) = N \cdot \left[1 + \lambda(\phi) \cdot \left(K_{coul}(\vec{q}) \cdot \left\{ 1 + \exp(-q_i q_j R_{ij}^2(\phi)) \right\} - 1 \right) \right]$$

6 radii: $R_o^2, R_s^2, R_l^2, R_{os}^2, R_{sl}^2, R_{ol}^2$



symmetry [Phys. Rev. C66, 044903 (2002)]: vanish at $y=0$
no 1st-order oscillations at any y , using 2nd-order RP



no symmetry rule against
 λ , oscillation, but keeping it
fixed reduces #parameters

small effect
(maybe more than gut intuition?)

can CERES and STAR be reconciled?

at this point, the energies measured are too close to reasonably expect such a difference.

What else could it be?

- different reaction-plane resolution correction technique?
- different centrality?
- different fitting parameters?
- different rapidity range? ← presently under investigation in data (models may help, too)

Table 2. Measurements of the anisotropic shapes from heavy ion collisions. The third column indicates which centrality bins were averaged to obtain the shape parameters of figures 6 and 7. See the text for details.

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New J. Phys. 13 065006 (2011)



summary & outlook

- asHBT in HIC: probe for non-trivial structure on the QCD phase diagram
 - unique, valuable information, but nontrivial analysis...
 - models show significant sensitivity to important physics
- growing systematics of asHBT over the past decade
 - intriguing possible minimum in $\varepsilon(v_s)$ not supported by preliminary STAR BES
 - other than CERES point, slow gradual decrease of eccentricity with v_s
 - any possible structure would be remarkably narrow
 - remarkable agreement with *prediction* of UrQMD
 - PHENIX pions at 200 GeV agree with STAR
 - PHENIX also reports kaons!
- outlook
 - rapidity study in STAR in continuing attempt to understand CERES and develop systematic errors
 - 1st-order, 3rd-order studies in STAR & PHENIX
 - ongoing asHBT studies in ALICE

